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DATE DUE

A TEXTBOOK OF GEOLOGY

BY

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PART I

GENERAL GEOLOGY

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DEDICATED

TO

MY FORMER STUDENTS

WHO

IN THE NEW WORLD AND THE OLD

ARE TRANSMITTING, AUGMENTING, AND APPLYING

THE KNOWLEDGE OF THE

EARTH SCIENCE

IN THE ACQUIRING OF WHICH

IT HAS BEEN MY PRIVILEGE

TO AID THEM

PREFACE

In the preparation of this book, I have departed somewhat widely from the prevailing order of treatment in current texts. Instead of beginning with the destruction of rocks, it has seemed more logical to give the student some knowledge of the rocks to be destroyed, and of their character and origin. Instead of treating clastic rocks first and igneous and other non-clastic rocks later, it has seemed more desirable to begin with those rocks from which clastics are largely derived, before dealing with the clastics themselves. Twenty years of experience as a teacher have convinced me that the average student admitted to courses in geology receives too little instruction in minerals, and although we generally recommend mineralogy as a desirable prerequisite, few teachers can insist upon a preparation in this subject on the part of the student. Yet without a knowledge of at least some minerals the study of rocks is impossible, and few geological phenomena can be adequately understood without at least a general knowledge of the rocks which they affect. Students who are preparing to make geology their life work, will in any case undertake a more extended study of minerals, and they will turn to the excellent textbooks in that science now available, and some of which are listed on page 51. But the great majority of students of geology come to this subject only with the desire to gain some knowledge of the world they live in, of the material of which it is composed, of the forces which have fashioned it, and of the laws which have governed its development. They may do so from a desire to master the secrets of nature for the material benefits to be derived from such a mastery, or for the power which such a knowledge will confer upon them; or they may undertake the study of the earth, because they wish to broaden their mental horizon and subject themselves to that stimulation of the intellect, that deepening of spiritual perceptions, and that awakening of dormant faculties, which others have found in a sympathetic understanding of, and love for, the out-door world, and which, in its fullest measure, is most frequently vouchsafed to the student of geology. From whatever motive the student approaches the subject, he should be made to realize that his desires can best be attained, if he keep in mind the maxim of La Rochefoucauld, "*Pour bien savoir une chose il faut en savoir les détails.*" Detail does not appeal to the

average student, but a knowledge of a certain amount of detail is necessary in any subject, if it is to be well understood, and in geology, as in other sciences, no real understanding of principles and of phenomena is possible without some conscientious devotion to detail. The book of nature is unsealed only to him who is willing to learn the language in which it is written.

I believe that at the very outset the student of the earth should subject himself to a moderate discipline in the elements of chemistry and mineralogy at least. To those who can not devote the time to separate courses in these sciences, Chapter IV may serve as guide for a series of laboratory exercises, which may be carried on simultaneously with the study in the classroom of the more general subjects treated in the first three chapters. In all such studies the individual teacher must select and amplify the subject matter; the text of Chapter IV is intended primarily as a guide, while to the student, already familiar with minerals, it may serve as a summary for convenient reference. In its preparation, and especially in the selection of the mineral species included in the tables, I have had the generous advice of the late lamented Professor Alfred Moses of Columbia University, and that of Professor L. Luquer of the same institution, while the experience gained in teaching mineralogy for a number of years at the Rensselaer Polytechnic Institute, at Tufts College and at the Museum of the Buffalo Society of Natural Sciences has been drawn upon. For reasons already set forth, I have next taken up the treatment of the igneous rocks. Many years of teaching elementary students both in college and in the summer sessions has satisfied me that while the study of rocks is carried on in the laboratory the broader relations of those rocks are advantageously treated at the same time in the lectures or classroom exercises. Therefore I would recommend that Chapter VI be used entirely as a laboratory text, while Chapters VII to IX inclusive serve for simultaneous classroom exercises, of course with proper material for illustration. Chapter X is again best treated as a laboratory text on aqueous (chemical) deposits, and here again each teacher will make his selection of material as time and equipment permit. Chapter XI serves as the accompanying text for lectures and classroom exercises, amplified and illustrated according to the teacher's predilections and equipment.

It has been my experience, as no doubt it has been that of many other teachers, that the study of rocks of organic origin requires some understanding on the part of the student of the types of organisms which are active in their production, and that the study of organic types should not be relegated exclusively to the chapters on historical geology. I therefore venture to hope that the introduction of illustrations of the various types of rock-forming organisms will be welcomed by the teacher,

and be of value to the student. Wherever possible I have selected illustrations of material easily obtainable, as in the case of the molluscan shells and several of the nullipores, which are common on our Atlantic coast, and in our rivers and lakes, and in that of the bryozoans and echinoderms (except the crinoids) which are easily obtained on our coasts. Most of the corals too are the common species found in, or easily added to, any collection. It is recommended that Chapter XII be used both as classroom and laboratory text. The same thing applies to Chapter XIII, which deals chiefly with the plants that enter into the construction of our peat and coal deposits, and specimens of these can readily be obtained by any one. Here, too, laboratory work with specimens and classroom exercises may go hand in hand.

The study of clastic rocks *per se*, treated in Chapter XVIII, may again be carried on in the laboratory during the simultaneous treatment of the forces which produce them and the phenomena of weathering, erosion, transportation, and deposition (Chapters XV–XVII) in the classroom and field. Although I do not suggest that these subjects be entirely ignored during the earlier part of the course, where the teacher may point out phenomena of weathering, stream and wave erosion, etc., especially during field exercises, I believe that systematic study is most satisfactorily deferred until non-clastic rocks, igneous phenomena, and other forces which produce material from which clastic rocks may in the first place be derived, have been considered. Other teachers may not agree with me and they may find it desirable to transpose the chapters. I have endeavored so to arrange the chapters that little if anything will be lost in effectiveness by their transposition, and to this end I have given repeated cross references. Therefore if the teacher so desires, he may pass from Chapter III directly to Chapter XV, taking up the intervening chapters in any order he deems fit.

I believe, however, that most teachers will agree with me that the broader subject of the sculpturing of the lands (Chapters XXII–XXIII, the essentially physiographic chapters) are best treated after, not only the formation and original structural characters of the earth's crust, but also its deformations have been studied. Although metamorphism by igneous contact has been treated in connection with the igneous phenomena, where it belongs, the main subject of metamorphism and metamorphic rocks (Chapter XX) follows the treatment of deformations (Chapter XIX) and may likewise be treated largely as a laboratory text.

Wherever possible, I have adopted the method of treating typical examples of geological phenomena in some detail, with an abundance of illustrations, because in my own experience, I have found that the student grasps the details of isolated examples more readily and more

completely assimilates them than he does generalizations with illustrations drawn from many sources, and from examples which are to him little more than names. On this account I have devoted more space than is usually given in textbooks to descriptions of well-known volcanoes, such as Vesuvius, Etna, etc., to a few typical glaciers such as the Aletsch, the Mer de Glace, the Malaspina, etc., to the Florida reefs and the Great Barrier reef, and to such special examples of complex rivers as the Niagara, the Genesee, and the Colorado. My choice of the types has been partly influenced by their accessibility, and it is my hope that the study of such accessible examples will awaken in the student the determination to study them in the field, a possibility any one may look forward to in these days of comparative lessening of distances. The same motive of treatment of types rather than facts and phenomena, has prompted me to devote what some may consider an undue amount of space to the details of the great historic earthquakes. I believe, however, that the human interest which these phenomena have, will appeal to the student, and he will duplicate my own experience, that such a narrative will give him a deeper knowledge of seismic phenomena than a categorical treatment of them could inculcate.

After due consideration and conference with the publishers, I have decided to use the old style of endings for the geological systems and periods, *i.e.*, Cambrian, Ordovician, Silurian, etc., instead of the more precise and uniform ending in *ic* (Cambric, Ordovicic, Siluric, etc.) which I have always maintained, and still believe, to be superior, not euphonically, but because they give uniformity to the terminology which has the hit and miss characteristics of a language grown up uncontrolled, and which is, therefore, not scientific. I am confident that in the future we shall adopt the system of uniform endings, and in my scientific writings I shall continue to use it where I can persuade the editor to permit it. In the present case, however, as the majority of teachers cling to the old terminology, I have, though with some reluctance, adopted it, more especially in view of the fact that it would make the use of the book more difficult if it did not conform to the language employed by the teacher. I desire, however, to have it distinctly understood that I have not surrendered my belief in the superiority of the more precise terminology, and that hereafter, as in the past, I shall continue to advocate its use.

For substantial assistance in the preparation of this text I am under obligation to a number of friends and colleagues. I have especially enjoyed the freely given advice of my former colleagues at Columbia University. The aid in the mineralogical chapter has already been referred to. Mr. Frederick K. Morris of Columbia read the proof of Chapters XV to XVII inclusive and made many valuable criticisms

and suggestions. A similar valuable office was performed by Professor C. P. Berkey for Chapters XIX to XXI inclusive, and by Professor D. W. Johnson for Chapters XXII and XXIII. To these gentlemen my best thanks are tendered herewith, and the assurance that much that may be valuable in these chapters is due to their advice, while for any divergence from their views, especially in the order and extent of treatment, I take full responsibility. The entire proof was read by Dr. Marjorie O'Connell of the American Museum of Natural History, and again by my friend Mr. Ernest Welleck of the editorial staff of the *Popular Science Monthly*, for whose gratuitously given and extremely effective service I gladly render full acknowledgment. My former student Miss Mary Welleck, A.M., has been my assistant throughout the arrangement of this text for the press, and has been of the greatest service in securing illustrations. She has a number of block diagrams entirely to her credit as acknowledged in the text, and also a number of other illustrations. Mr. Frederick K. Morris has also contributed several of his effective drawings, and has made special effort to secure photographs as elsewhere acknowledged. To Miss Florence Holzwasser of Barnard, I am also indebted for careful work in comparing manuscript and copy, and to Messrs. C. J. Connelly and F. K. Morris and to Dr. J. J. Galloway for reading part of the text and making suggestions.

To Miss Amy Hepburn, Librarian of Natural Science in Columbia, and to the geological, botanical, and zoölogical libraries of that University I am under special obligation for freely furnished material for illustrations. Prof. J. F. Kemp has generously loaned his portrait of Werner. The United States Geological Survey has furnished a large number of original photographs from which illustrations were made for this book, and Dr. D. W. Johnson of Columbia has placed his entire collection of photographs at my disposal for selection of illustrative material, and I hereby record my great indebtedness to Dr. Johnson and to Dr. George Otis Smith, Director of the Federal Survey, for their courtesy. To Dr. John M. Clarke and the State Museum at Albany I am likewise under obligation for several illustrations in this part of the text and for many more in Part II. The geological department of Harvard University has generously loaned me a number of photographs from the Gardner Collection through the chairman, Prof. R. A. Daly. To Prof. J. B. Woodworth of that University I am also indebted for several original photographs. The Alaska Engineering Commission has also generously furnished a number of photographs of glaciers through Mr. W. A. Ryan. Prof. Elizabeth Fisher of Wellesley College has furnished several very effective photographs taken by herself and others as acknowledged in the text. From Prof. W. H. Sherzer I have received prints of his photographs of sand grains reproduced in Grabau

and Sherzer's *Monroe Formation of Michigan.* A number of photographs were taken by Dr. Marcus I. Goldman (U. S. G. S.) during a trip with the author in England and Scotland under the guidance of Dr. Benjamin Peach. Several were taken by Mr. G. W. Stose (U. S. G. S.) during an early trip in company with the author, in Nova Scotia. The Philippine Bureau of Science, at Manila, Dr. Elmer D. Merrill, Director, has generously furnished the fine photograph of Mayon Volcano reproduced in the frontispiece. Prof. W. O. Crosby has furnished a number of illustrations used by him in his illustrated Museum Guide (*Dynamical and Structural Geology*, Boston Society of Natural History, 1892), and a number of photographs of geological features in Utah have been received from Prof. F. J. Pack of the University of Utah. To all these contributors my best thanks are given. To The American Museum of Natural History my thanks are gladly given for the fine photograph of the eel-grass in the Annulate group, constructed by Dr. Roy Miner and reproduced in Fig. 274, and for the photographs of the Spine of Pelée (Figs. 106, 107) taken by Dr. E. O. Hovey. The American Geographical Society, through its director Dr. Bowman, also generously loaned a number of cuts as elsewhere acknowledged, and the *Popular Science Monthly* has furnished a number of photographs for reproduction. Others to whom I am indebted for furnishing original photographs are Dr. C. P. Berkey, Miss A. D. Savage, Dr. M. O'Connell, Dr. Elsworth Huntington, the late Prof. C. S. Prosser, Dr. C. C. Mook, and my brother Mr. P. L. Grabau. My former student Dr. Bela Hubbard has prepared a number of photographs of rocks and rock structures from original specimens and thereby put me under great obligation. To Messrs. Dodd Mead and Co., Ginn and Co., Henry Holt and Co., The Macmillan Co., John Wiley and Sons, and to Yale University Press, publishers of *Military Geology*, I am indebted for permission to reproduce illustrations from books published by them. These are acknowledged in the text, as are also the sources of other illustrations, — especially Kayser's *Lehrbuch;* Lake and Rastall, *Textbook of Geology;* Le Conte, *Elements of Geology;* De Martonne, *Géographie Physique;* Rosenbusch, *Elemente der Gesteinslehre;* Lyell's *Principles;* Ratzel, *Die Erde;* Gray's *Botany;* Davis, *Erklärende Beschreibung der Landformen;* Haug's *Traité;* Merrill's *Contributions to the History of American Geology;* Verrill and Smith, *Invertebrates of Vineyard Sound;* Binney and Gould, *Invertebrates of Massachusetts;* and books by Walther, Haas, Bowman, Geikie, Zittel, Steinmann, Krümmel, Murray, Heim, Suess, J. M. Arms-Sheldon, and others. To the publisher of my *Principles of Stratigraphy*, and of *North American Index Fossils*, Mr. A. G. Seiler, I am indebted for permission to reproduce a number of illustrations from these works. Prof. Moses generously permitted the

reproduction of a number of illustrations, especially of crystal outlines, from his *Elements of Mineralogy*, published by D. Van Nostrand Co. Finally, my sincere thanks are due to my publishers, Messrs. D. C. Heath and Co., for their generosity in giving me a free hand in the selection of illustrations, in placing no limit upon their number, and in furnishing a considerable proportion of them.

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TEXTBOOK OF GEOLOGY

PART I — GENERAL GEOLOGY

CHAPTER I

INTRODUCTION

The Science of Geology

Definition. — Geology is the science of the earth in all its aspects, except those which deal with the relationship of the earth to other planets and to the sun of our solar system. That aspect of the earth properly belongs to the science of Astronomy, for our earth is one of the heavenly bodies with which that science is concerned. It is true that this phase of the subject is often treated by the geologist under the name of *astronomical geology*, but in this book we shall consider it as belonging primarily to the field of astronomy. At the same time we shall recognize the importance to the student of at least a general understanding of these astronomical relations of the earth, and consider such an understanding a desirable preliminary preparation.

Derivation of Terms. — The term Geology is derived from the Greek words *ge* (γῆ), earth, and *logia* (λογία), science, or logical discourse. The science of geology was preceded by and in a measure grew out of the subject of geography, which literally is the description of the earth (*graphein*, γράφειν, to write) and was, of course, chiefly confined to a description of the earth's surface features, and their significance in terms of human existence. But since surface features are generally the expression of underlying structure, and of the geological history of the region, it is evident that geography cannot be divorced from geology, and that, to no inconsiderable extent, the student of the geography of a region must take account of its geological structure and history.

Scope of Geology. — In its broadest sense, then, geology is the science of the earth and all that pertains to it. It is the study in

detail of one of the planets in one solar system, by the inhabitants of that planet, who are themselves a part of it. If other planets of our solar system or those of other solar systems are inhabited, the study of those planets by their inhabitants would correspond to our geology — it would be the science of a particular planet. By us little can be ascertained regarding the structure and development of other planets, except in an indirect way, — and all investigations along such lines fall properly into the domain of the astronomer, though he concerns himself primarily with interrelations of the heavenly bodies. And thus we may consider that the study of the physical universe, *i.e.*, the *cosmos*, which may be called the science of *cosmology*, has only the two primary divisions, astronomy and geology. This may be summarized as follows:

COSMOLOGY The science of the universe	1. *Astronomy.* — The science of all the heavenly bodies, including the earth, their character, distribution, interrelations, movements, etc., and the laws which govern them. 2. *Geology.* — The science which deals with the material, structure, history, etc., of one of those bodies, *i.e.*, the earth.

Such a view of the science of geology gives it an extremely comprehensive scope, and we must recognize that in ordinary parlance the term is used in a much more restricted sense Nevertheless it is desirable to take this comprehensive view at the outset, and to note the several subdivisions into which such a broad science naturally falls, and with all of which the student of any one division should have at least a general acquaintance. We shall best get the proper view-point by first considering the earth in its entirety.

THE EARTH VIEWED AS A WHOLE

Could we view the earth in its entirety from some extraterrestrial vantage point, we would recognize it as an oblate spheroid, that is, a body approaching that of a sphere, but with its polar diameter flattened and its equatorial belt somewhat inflated. By measurement the polar diameter of the earth is found to be 7899.7 miles, while the equatorial diameter is 7926.5 miles. If the observer in extraterrestrial space is sufficiently removed from the earth's surface, that surface would appear essentially smooth, as does the surface of the moon to our unaided eyes; the irregularities which the dweller on the earth recognizes as mountains and valleys would

become of insignificant proportions. Were we to represent the earth by an accurately scaled model 10 feet in polar diameter, the equatorial diameter would exceed the polar by only a trifle over $\frac{4}{10}$ of an inch, while the highest mountains on the earth's surface would form elevations on the model less than $\frac{3}{32}$ of an inch in height. Thus viewed, the prominences which appear to us formidable are after all of minor significance, and bearing this in mind, we can understand that relatively slight bulgings or crumplings of the earth's surface may produce what to us appear as great elevations. The wrinklings on the skin of a drying apple constitute far more prominent elevations in proportion to the size of the apple than do the highest mountain chains on the earth's surface, when compared with the size of the earth, while the scratches and notchings formed upon the surface of a glass marble, after a brief play, form vastly greater depressions, in proportion, than do the largest river cañons, such as that of the Colorado, or the deepest ocean depressions. Thus when the geologist finds evidence that the summit of the high peaks of the Himalaya Mountains or the top of the Apennine chain were once a part of the sea-bottom, he no longer concludes that the sea once covered these mountains, as was formerly supposed, but he infers rightly that these mountain chains were raised by a wrinkling of the earth's crust or by an upward warping which occurred at a time subsequent to that in which this region was beneath the sea. The evidence from the material of the mountain which leads the geologist to such a conclusion will be discussed in subsequent chapters, and the corroborative evidence from the structure of the mountains will also be given. The chief lesson which it is intended to impress upon the student at present is that surface features are relatively unimportant when we consider the earth as a whole, and that elevations and depressions — except those which we recognize as continental masses and oceanic depressions — are of local significance chiefly, and may change from one to the other not once but many times.

> There rolls the deep where grew the tree.
> O earth, what changes hast thou seen!
> There where the long street roars hath been
> The stillness of the central sea.

This is more than the expression of the poet's fancy; it is a truth which the observation of the earth and logical deductions from these observations force upon the geologist's attention at every step.

The Successive Inorganic Shells or Spheres of the Earth

The Spheres Open to Direct Study. — The observer from his extraterrestrial view-point will, however, note clearly that a large part of the earth's surface — to be precise, about 70.8% of it — is covered with water. This is the sea which is divided into a number of oceans and surrounds all the lands, and, moreover, forms a continuous body, the surface of which comprises approximately 137,070,000 square miles or 361.1 million square kilometers. The land has a surface area of about 59,870,000 square miles or 148.8 million square kilometers, giving a total surface area for the earth of 196,940,000 square miles or 509.9 million square kilometers. Certain portions of the land surfaces are also covered by water bodies, the lakes, which are not in direct connection with the sea. Among these the Great Fresh-water Lakes of North America, and the Caspian, a great salt-water lake, are the most prominent examples. These are to be classed as a part of the land, as continental water bodies, distinct from the sea. Moreover, the upper layers of the land in nearly all parts are water-bearing, this water filling the empty spaces of the soil, and occupying the pore-spaces within the solid rock. This is the *ground water*, which is tapped by wells, mines, or borings, or issues on the surface in springs which feed the brooks or rivers, or form swamps, ponds, and lakes. It is thus possible to speak of a nearly or quite continuous mantle of water which completely covers some parts of the solid surface of the earth and more or less completely saturates the exposed parts. This mantle of water may be viewed as an aqueous sphere enveloping the rock sphere of the earth and it is spoken of as the *hydrosphere*. It in turn is enveloped by the sphere of gas and vapor, the well-known *atmosphere*.

These two spheres or shells constitute the outer layers of the earth thus viewed in its entirety, and surround the more rigid mass of the earth, with which we are most familiar. This consists of solid rock, and of unconsolidated soil and other loose material, all of which, except the surface film of organic matter, we may recognize, on examination with a magnifier or by other means, as broken-down rock material in a fine state of division. From observation of soundings, dredgings, etc., and by inference, we know that similar material forms the ocean floor, and thus we recognize that beneath the hydrosphere is a sphere or a shell of rock material. This

is called the rock sphere, or *lithosphere*, and in it are included all of the soil and other unconsolidated rock material of the earth's surface. How thick this shell of rock is, we have no means of knowing from observation. The deepest borings into the earth's crust have penetrated only a little over a mile in depth, while the deeper mines go less than two miles beneath the surface. But from logical deductions of many observed physical facts, we conclude that this shell has a thickness of at least 75 miles, and perhaps much more. It is indeed generally held that the earth is solid rock to the core, but there are those who have held, and some who still hold, that the central portion of the earth consists of fluid or perhaps even of gaseous matter.

There are thus three inorganic spheres, the *atmosphere*, the *hydrosphere* and the *lithosphere*, open to partial observation. The relationships and relative magnitudes are shown in the following diagrams (Figs. 1 *a* and *b*).

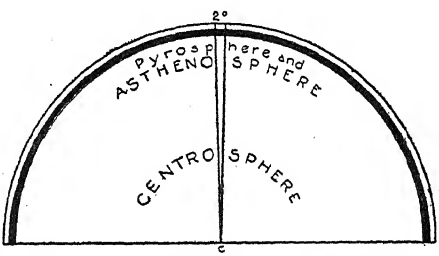


FIG. 1 *a*. — Diagram of the successive inorganic spheres of the earth. The heavy black line represents the lithosphere, including the hydrosphere, taken as 75 miles. The white semicircle above it indicates the atmosphere. *C*, center of the earth. The part included between the two radii, 2 degrees apart, is enlarged in Fig. 1 *b*.

The Inner Spheres. — From the observation of many phenomena, geologists and physicists have reasoned that beneath the lithosphere, other spheres characterized by certain peculiarities may be recognized, though their boundaries are variable and probably not very definite. One of these is the sphere or zone in which the temperature of the earth is sufficiently high to permit the fusion of rock if the pressure, which ordinarily keeps it solid by raising the fusing point, were removed or lowered by some structural change in the earth's crust. There may be regions in which essentially permanent pools of molten rock exist within the crust, forming feeders of volcanoes, but the majority of such feeding areas are more probably temporary. It is convenient to speak of this more or less concentric zone as a distinct sphere and the name *pyrosphere* has been applied to it.

Another equally indefinite sphere or zone, variously regarded as

lying from 30 to 75 miles beneath the surface (according to our estimate of the thickness of the lithosphere), is one of relative weakness, between a strong external crust and a rigid central mass. Here the rock yields most readily under long-enduring strains of limited magnitude, and earth-movements, resulting in the deformation of the rocks, occur. This zone or sphere, which has been called the *tectosphere* (Murray) or the *asthenosphere* (Barrell), may in part include the pyrosphere; nevertheless, it is convenient to speak of it as distinct.

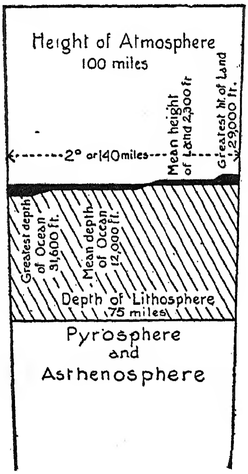


FIG. 1 *b*. — Enlargement of a part of the sector shown in Fig. 1 *a*, to show the relative thickness of the crust of the earth, the mean and greater depths of the sea and the mean and great heights of the land. Approximate scale 1 inch = 110 miles. On this scale the two radii meet at a distance of about 3 feet from the surface of the hydrosphere (black) this point then representing the center of the earth.

Finally there remains the central portion of the earth, the *centrosphere*, which is by far the largest part of it, and about which we know nothing from observation and but little from inference. From the known rate of temperature increase in borings and mines, it is inferred that the temperature near the center of the earth may be between 200,000 and 350,000 degrees Fahrenheit, a temperature so high that were it not for the enormous pressure, all the rocks there would probably be vaporized. From the fact that the average specific gravity of the rocks which constitute the earth's crust is only about 2.6 while that of the earth as a whole is 5.6, it is further inferred that the material of the centrosphere is very heavy and it has been calculated that if there were a steady increase in the specific gravity of the material from the surface toward the center, this would, at the latter point, become 11.2, which suggests the possibility of a central core of iron, if not of gold and platinum or some other heavy metal. Because of this greater weight, the centrosphere is also spoken of as the *barysphere* or heavy sphere.

The Organic Sphere or Biosphere

To these inorganic or lifeless spheres there is added the organic sphere, or sphere of life, the *biosphere* (*bios*, *βίος*, life). It would surprise the average student could he see the universality of this organic shell of the earth. In and out among the mass of the water and of the air and upon and through the upper layers of the rocky surface, the thread of living matter is woven, now constituting an almost solid mass of tissue, as in the bodies of peat or in the dense vegetation of a forest, or the almost continuous tangle of seaweed or layer of floating organisms in the sea; again forming a network, the meshes of which vary greatly in size, but are on the whole continuous, except where momentarily broken by the hand of man, or by some abrupt, not to say cataclysmic disturbance, such as an avalanche or outpouring of a mass of lava. But left for even a short time, the steepest quarry wall, or the most precipitous cliff formed by the sudden dislodgment of a mountain side or by the sinking of a portion of the earth's crust, such as may take place during an earthquake-producing disturbance, will be again taken possession of by some form of plant, if not of animal life. Even the stony lava field will be covered in time by a succession of organic forms of increasing complexity. The apparently barren desert, too, has its wide-meshed net of living beings, except perhaps where the sands are constantly in motion; and the presence of these organisms is often shown by the countless tracks and trails which appear upon the surface of the sand on a dewy morning, or the sudden springing up of vegetation from hidden seeds when moisture furnishes the condition for expansive growth. And in the sea, life of some form is never wanting long, — here covering the bottom with a continuous living carpet, there forming an ever changing web of floating animal and plant life, through which the swimming world of animals weaves an intricate pattern with the threads of its never ceasing wanderings.

Thus it is perfectly in accord with the facts, when we speak of a shell or sphere of living matter, the *biosphere*, which surrounds the lithosphere and penetrates its upper layers as well as the hydrosphere and the atmosphere, but is distinct from all. That such a biosphere has existed throughout most of the past ages of the earth's history is clearly shown by the countless remains of the hard parts of animals, such as the shells of mollusks, the bones of vertebrates

and the like, which fill many of the rocky layers of the lithosphere, and indeed sometimes actually compose these layers. For example, the white chalk of the English and French coastal regions is literally made up of the shells, and fragments of shells, of organisms (Foraminifera, coccoliths, etc.), as shown in the following illustration (Fig. 2), and many of our great limestones are consolidated remains of shells of animals which formerly inhabited the seas, or fresh-water lakes. In the following figure (Fig. 3) is shown an enlargement of a group of minute needle-like shells, each one of which was built by a separate marine animal and of which a limestone, traceable over wide areas in the state of New York, is almost entirely composed. From careful study, it has been determined that a cubic inch of this rock, when pure, contains about 40,000 individual shells (J. M. Clarke).

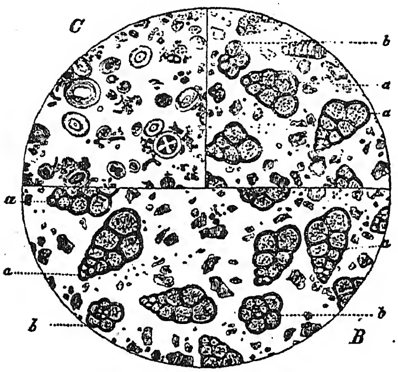


FIG. 2. — Thin sections of chalk, as they appear under the microscope, showing the shells etc., of minute marine organisms (chiefly Foraminifera and coccoliths) of which the rock is composed. *A*, Chalk from Sussex, England, enlarged 60 times. *B*, Chalk from Farafrah, Libyan desert, enlarged 60 times; the most characteristic shells are Textularia (*a*) and Rotalia (*b*). *C*, Dried residue of milky chalk water with coccoliths enlarged 700 times. (After Zittel.)

Whole mountains are sometimes made up of rock, which is largely, if not entirely, the product of accumulation of the hard structures of former organisms. An example of this is found in the famous Dolomites of the Tyrol (Fig. 4), the chief rock masses of which are made up of calcareous matter separated from a sea by marine plants (Fig. 5), and the many centuries of time during which the present forms of these peaks were carved from this

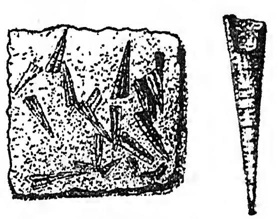


FIG. 3. — *Styliolina fissurella*, a minute molluscan (pteropod) shell. Fragment with numerous individuals enlarged three times; and a specimen much enlarged. (After Hall.)

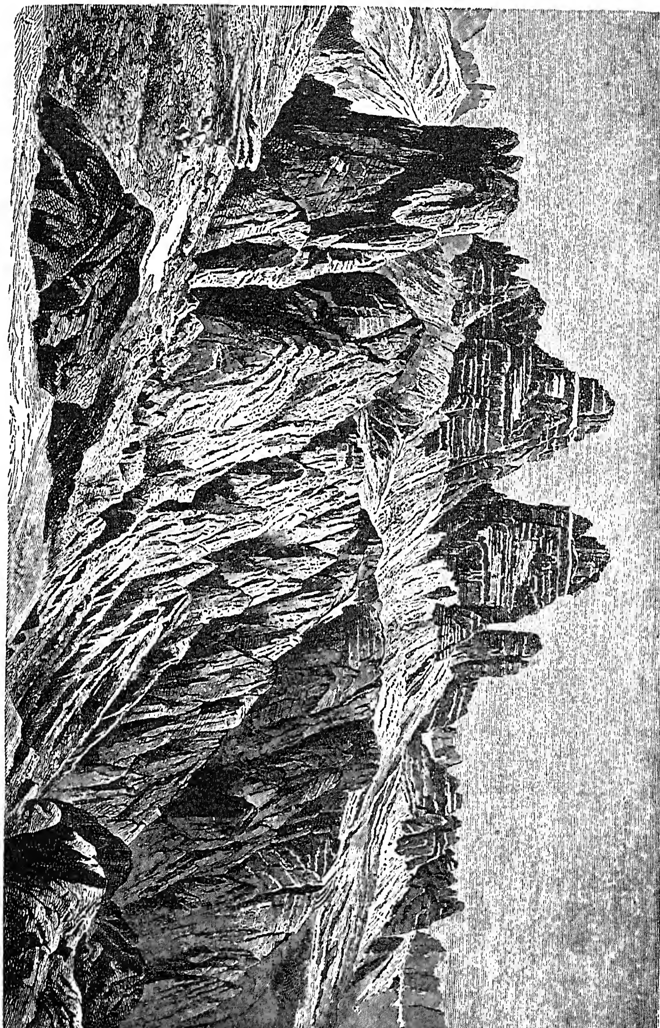


Fig. 4. — View of "The Dolomites," with the Drei Zinnen peaks, near Schluderbach in Tyrol. After a photograph (from Ratzel). The rock of this mountain mass is made up largely of the remains of lime-secreting marine plants or algæ of the type shown in Fig. 5.

rock have witnessed only a partial obliteration of the organic structures, though no inconsiderable portion of the mass has been removed.

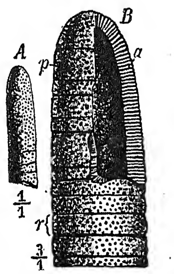


FIG. 5. — *Diplopora porosa* Schafh. A calcareous alga or marine plant which was chiefly responsible for the making of the rock out of which the Dolomites are carved. *A*, Natural size. *B*, enlarged 3 times. *a*, canals which appear upon the surface as pores, *p*; *r*, constricting rings characteristic of this genus. (After Steinmann.)

The remains of animals and plants which compose, or are included in, the rocks of the earth's crust, are known to the geologist as *fossils* (from the Latin *fossilis*, something that is dug up) and their study forms an important and integral part of the science of geology. It is indeed the study of the constantly changing elements of the biosphere, of which the existing animals and plants form only the most modern phase, that has made possible the deciphering of the history of the earth. This subject will be more fully considered in later chapters of this book.

Beds of coal, too, point to the former extensive accumulation of vegetable material, and the oil of our oil shales and pools owes its origin largely, and perhaps altogether, to the distillation, during many centuries of time, of buried organic matter which constituted a portion of the biosphere of former geological periods.

Contributions to the Lithosphere from Other Spheres

We now see that the biosphere contributes no inconsiderable portion to the growing lithosphere, and this is true to a certain extent also of several of the other spheres. For not only was the carbon of ancient plants, which is now locked up in the earth's crust as coal and oil, contributed by the atmosphere of the past, but the water vapor of the air, freezing and descending as snow or hail, or crystallizing directly upon cold surfaces, forms a not unimportant, though in most regions very transitory, addition to the solid rock of the earth. So, too, the conversion of water to ice forms rock at low temperature, for ice is a rock. More permanent contributions are made by the crystallizing of various salts, chief among them the common salt (sodium chloride), which, as we shall see later, may become buried by other rock material, and be preserved

for millions of years as an essential part of the earth's crust. Thus the salt now mined in New York State and in southeastern Michigan was derived from the waters of an ancient sea, the derivation being by a roundabout process, which will be detailed later. That this occurred in a period of time many millions of years ago is amply shown by the ascertainable facts. So, too, the great salt deposits of North Germany, which have furnished the world in the past with most of its potash, are the product of the evaporation of cut-off portions of an ancient sea which covered much of Europe, though the period of its production is not quite so remote as that of the best-known American salts. (See Chapters XXXIV and XXXVIII.)

That the pyrosphere also contributes its quota to the rock mass of the earth is abundantly shown by the vast extent of ancient lavas and other igneous masses which now form a large proportion of the solid crust of the earth and are visible to us as the result of surface cooling in comparatively modern times, as in the case of the great Columbia lava fields of Northwestern America and the preserved fragments of similar flows on the British coast (Staffa, Giants' Causeway, etc.), or which were uncovered by the removal, during long geological epochs, of the overlying portions of the earth's crust beneath which the ancient igneous masses assumed their solid form.

Throughout the entire history of the earth, the lithosphere has received additions by the cooling of molten rock material injected into it or poured out on its surface, and this addition is in progress even to-day.

Contributions to the Lithosphere from Outer Space

Finally it may be added that the earth's crust receives to-day, and undoubtedly has received in the past, additions from the cosmic spaces which surround our atmosphere. When a meteor reaches the earth it forms an integral part of the unconsolidated or *discrete* portion of the earth's crust, at least until it is gathered in by the discerning collector of these messengers from the extraterrestrial spaces.

Summary of Spheres

We may now summarize in tabular form the several spheres or shells into which the earth as a whole is divisible, and add to this summary the derivation of their names.

A. The Inorganic Spheres, (σφαῖρα) = sphere.

1. Atmosphere, Gr. *atmos* (ἀτμός) = vapor or gas.
2. Hydrosphere, Gr. *hydor* (ὕδωρ) = water.
3. Lithosphere, Gr. *lithos* (λίθος) = stone.
4. Pyrosphere, Gr. *pyr* (πῦρ) = fire.
5. Asthenosphere, Gr. *asthenos* (ἀσθενής) = feeble.
6. Centrosphere, Gr. *centron* (κέντρον) = center, *or* Barysphere, Gr. *barys* (βαρύς) = heavy.

B. The Organic Sphere.

7. Biosphere, Gr. *bios* (βίος) = life.

CHAPTER II

SUBDIVISIONS OF THE SCIENCE OF GEOLOGY

It is but natural that the mind of man, always eager to enter into details, should have developed distinct branches of inquiry into the character and history of the several parts of the earth which is his home. In the beginning of such inquiry, a single master mind may have encompassed the entire field; but with the increasing mass of detail, the individual range became limited to special portions of the field, and in the course of time the several lines of inquiry into the nature and history of our earth developed into distinct sciences, each with its host of devoted searchers after truth.

Subdivisions of the Science in its Comprehensive Sense

We may, then, at this point of our study, endeavor to ascertain the natural subdivisions of the Science of the Earth, or Geology in its broadest sense, and after that confine ourselves to those branches which by common consent are reserved as the special field of the geologist, as it is understood at the present time.

Atmology or Meteorology. — From an inspection of the table of spheres into which the earth may be divided, we form the natural conclusion that the first line of cleavage would be in accord with these natural subdivisions. The study of the atmosphere has now developed into a separate science, which is familiarly known as *Meteorology* because the meteors, or extraterrestrial bodies, the familiar "shooting stars," which on entering our atmosphere become luminous through friction and frequently reach the earth as meteorites, have from the remotest days formed one of the chief attractions for those whose gaze was turned away from the solid earth. Thus atmospheric phenomena came to be designated as meteoric phenomena and the science of these phenomena became meteorology. But since the sphere with which this science is concerned is the *atmosphere*, a more appropriate name for this science itself is *Atmology*.

Hydrology. — That the hydrosphere, that is, the oceans and other water bodies, early attracted the serious-minded student was but natural, since these water bodies form the natural highways of commerce, and since they furnish so large a part of the earth's population with the means of a livelihood. Thus the science of the water, or *Hydrology*, was developed, which is variously subdivided again into the sciences of the oceans, or *Oceanography*, and into the sciences of the lakes, the ponds, and the rivers. That some of these, for example oceanography, have been developed to a remarkable extent, is shown by the great oceanographic institutes of the world, of which that of Berlin under Director Penck, and that at Paris, under the direction of the Prince of Monaco, are the best known. In America, oceanographic studies have chiefly been carried on by the federal government and by private individuals, among these the late Alexander Agassiz; and there is a hydrographic department of our government, the chief business of which is the charting of our sea-coasts, lakes and rivers.

In England, too, oceanographic studies have been largely fostered by the government, under whose auspices the famous *Challenger* Expedition, for the exploration of the oceans, under the leadership of Sir John Murray, was carried to successful completion. The governments of other countries, too, have fostered exploring expeditions for oceanographic research, these being generally known by the name of the vessel employed in the expedition.

The student of geology, even in its narrower sense, must keep abreast of these inquiries, at least to a moderate extent, for without them many of his discoveries lack the clarifying light by the aid of which he must interpret them; and in proportion as the researches of the oceanographers and the other hydrologists become available, the analysis of the structure and composition of the earth's crust, the special field of the geologists in the modern sense, and the interpretation of these facts in terms of earth history, become more precise.

Lithology or Geology Proper. — As has just been said, the special field of inquiry of the modern geologist is the crust of the earth, or the *lithosphere*. He is thus primarily a student of *Lithology* — though that term has also been used in the past in a narrower sense, the study of rocks *per se*. It will be well, however, for the sake of unity of terminology — a great desideratum in every science — to adopt this term in its wider sense, namely, that which encom-

passes all the fields of inquiry which are concerned with the composition, structure, and history of the earth's rocky shell, the *lithosphere*, generally assigned as the only legitimate field of the modern geologist. Still, to-day more than ever, the geologist cannot limit his inquiries to the facts disclosed by the rocks alone, but must draw his conclusions with the aid of a wide knowledge of the researches of the atmologist, the hydrologist, and even the biologist.

Biology; Palæontology. — Biology is the science of living things. It is the study of the *biosphere*, and has perhaps been more sedulously developed, and has a larger body of votaries, than any other branch of the earth science. Biology, as currently understood, limits itself to the study of modern living beings, the plants and animals of to-day, and naturally falls into the two divisions, or separate sciences, of *Botany* (Phytology [1]), the study of plant life, and *Zoology*,[2] the study of animal life. Biologists are, however, aware of the fact that the modern world of plants and animals is only a fragment of the great host of living beings which has inhabited the earth from the remotest ages; it is the life record of the youngest and shortest chapter in the history of the earth. Throughout all the past ages, living forms existed upon the earth, and their remains, as we have already seen, are embedded in the rocks of the earth's crust as *fossils*. The study of these was at first left to the geologist, but has now developed into a separate science, that of *Palæontology* (from the Greek *palaios* [παλαίος], ancient, *onta* [ὄντα], living beings, and *logos* or *logia* [λογία], science).

Other Divisions. — When we come to the consideration of the inner spheres of the earth, we must admit that, owing to our inability to make direct observations, no separate sciences worthy of that designation have yet been developed. It is true that a science of earth disturbances or *Seismology* exists, and that this properly belongs to the study of the asthenosphere or tectosphere. But the observations on which this science is based are chiefly possible upon surface manifestations and the effects which these produce, though inferences can also be drawn from the study of disturbances which have occurred in the past, the effects of which are recorded in the rocks. The same is true of the study of the pyrosphere — which can only be approached through observa-

[1] Greek *phyton* [φυτόν], plant.

[2] Greek *zoön* [ζῷον], animal.

tions of modern volcanoes (*Vulcanology*) and of the temperatures in deep borings and mines. Of the interior of the earth we may perhaps never know much through observation, and so deductions from physical phenomena alone must guide us. No separate science of the centro- or barysphere has thus been developed.

From the foregoing, the student is led to the realization of the truth that all true sciences are based on two great fundamentals, *observation* and *deduction*. To observe and record facts alone does not constitute the whole of the work of the man of science. Such used to be the sole aim of the older naturalists, so called, who dissented from the attitude of the ancient philosophers, because these based their speculations on mental processes rather than observation of facts. To-day, however, we know that the interpretation of facts, in the light of our growing knowledge of causes, is as legitimate, indeed as important, a function of the student of the earth as the observation of facts, and moreover a certain amount of speculation — always held in check by the appeal to facts — is not only desirable but necessary. The student of nature must be a philosopher in the true sense of the word, and so long as he does not lose sight of his fundamental base — the observation of facts — his work will gain in value by allowing his reasoning faculties their fullest play.

Subdivisions of the Science of Geology in its More Limited Sense. Lithology or the Study of the Lithosphere

Restricting our attention now to the more limited field to which the modern geologist applies himself, namely the study of the material, structure, and history of the earth's crust, or the lithosphere, we may note at the outset that there are two phases or aspects of this field, one or the other of which is cultivated more sedulously by the geologist according to his predilections or circumstances, but neither of which can be wholly neglected by the worker in either field. These two aspects are the purely scientific, and the practical or applied. The geologist who works in the pure science field of his domain does so primarily for the intellectual satisfaction derived from the discovery of facts and principles. His aim is chiefly to search for nature's truths irrespective of their bearing on human welfare, and his principal endeavor is directed toward widening the boundaries of human knowledge and pushing forward

the frontiers of discovery. The chief aim of the practical geologist, on the other hand, is directed toward making the forces and materials of the world available to man, to augment the welfare of the human race, and to push forward the boundaries of civilization. But this work, important and noble as it is, can only be carried on successfully in proportion as the facts and laws of the science are discovered and demonstrated, and the practical geologist must forever depend on the worker in pure science, whose reward too often is little more than the satisfaction which is to be derived from a devotion to the search for truth. We shall for the sake of convenience speak of the pure-science phase of our subject as *the scientific aspect of geology*, and of the applied phase of geology as *geology in its relation to man.* Each phase has its special subdivisions, to which attention may now be drawn.

I. *The Scientific Aspect of Geology*

Structural Geology. — A logical analysis of this field of investigation reveals a threefold aspect and three corresponding methods of approach in study. In the first place the material of the earth's crust, and the composition and the structure of this material, invite attention. This portion of the subject is generally treated under the caption *Structural Geology.* It takes account of the composition, form, and architecture of the earth's crust, and is primarily an analytic branch of the science. From this point of view the earth's crust may be considered under the following subdivisions, given in the order of their magnitude.

Subdivisions of Structural Geology. — These include the following fields:

1. Chemical elements and ions.

2. The combination of these elements and ions into salts and other compounds which either take on crystalline form or remain in an uncrystalline (amorphous) condition. These compounds as they occur in nature are designated **minerals**.

3. The combination of crystals or fragments of the same or different minerals into large masses, either bound together into a more or less solid mass, or remaining in an unconsolidated condition. These are the *rocks* of the earth's crust, and for their study a recognition of at least the principal component minerals is essential.

4. The association of rock masses into original or primary *structural units*, which constitutes the primary *architecture* of the earth's crust; or the impression upon it of *secondary structures*, through deformation or other influences of an outside nature. This is structural geology in the narrower sense — and has also been called *Geotectology*. The original structure corresponds to the initial architecture of a building, the stones or bricks of which correspond to the rock masses of the earth's crust. The secondary structures correspond to the changes subsequently made by additions, removal or modification resulting from sagging with age, etc.

5. The surface forms resulting through the activities of destructive as well as reconstructive forces, and recognizable in the mountains and valleys, the plains and plateaus, and other physical features, generally considered under the subject of *Physical Geography*. The term *Geomorphology* — or the study of the details of the earth's surface forms — has been commonly applied to this branch of inquiry, when it is not merely descriptive or analytic, but takes account of the history or genesis of the form as such. It corresponds to the study of the form of a building as a whole, either in its completeness or when changed to a ruin by destructive influences.

The study of most of these divisions of structural geology has been carried to such detail that separate sciences have been developed. Thus the study of the natural substances, or minerals, has become the science of *Mineralogy*, and that of the rocks the science of *Petrology* (also sometimes designated as lithology in its narrower sense), while the science of rock structures is *Structural Geology* in the narrower sense, and that of the surface forms is *Physiography*, and their relation to man is *Geography*.

In all such studies, while emphasis is laid on the analytical and descriptive sides, the causal or dynamic side and the historical or developmental side are given their due attention. This is expressed by the preference of terms ending in *ology* (mineralogy, petrology, geotectology, geomorphology) over those ending in *graphy* (petrography, physical geography, etc.), which emphasize mainly the descriptive and analytical side.

Dynamical Geology. — A second mode of approach is that which lays the emphasis upon the forces that work upon and within the earth to produce results, which, in this view, take a secondary rank. This is *Dynamical Geology* and it naturally falls into the two great

divisions, the *physical* and *chemical*. The sciences of physics and chemistry, in so far as they lay the stress upon the forces at work, are the specialized development of these aspects. That chemistry, in its analytical as well as its dynamic aspects, is of fundamental importance to the geologist has generally been recognized, but the importance of physics to the student of earth science has only recently received proper recognition by the establishment of geophysical laboratories.

Both *chemical* and *physical* forces may be viewed as *constructional*, or those building up rock masses and rock structures, and as *destructional*, or those destroying them. A third view of these forces is that which deals with their effects in modifying or deforming the materials and structures, and this may be termed the *reconstructional* or deformational aspect.

Historical Geology or Geogenesis. — The third method of approach is the historical or evolutionary method, in which emphasis is laid upon development and the causes which underlie this development. It is apparent that this phase of geology is the latest and most specialized aspect, and that for its proper prosecution a thorough preparation in the other two phases is needed. Moreover, since the history of life upon the earth is intimately bound up with the history of the lithosphere, a knowledge of biology, and especially of palæontology, is indispensable for the prosecution of any but the most general studies in earth history.

Several special branches have been developed within this field. One of these deals with the origin or genesis of the rocks and their structures, or the origin of the lithosphere. To this branch the name *Lithogenesis* is commonly applied. Another branch considers the character, arrangement, succession, order of formation, and age relations of the stratified rocks. This is the science of *Stratigraphy*, primarily a descriptive one. A third branch deals with the succession and distribution of the organic remains, the petrifactions or fossils in the rocks in so far as they have a bearing on the geological history of the earth, *i.e.*, the *index fossils*. This is the special geological phase of *Palæontology*, which has also been designated by the name *Petrifactology* (Haeckel). Again, there is the science which deals with the development or genesis of the surface forms of the earth not merely in the descriptive manner, but from the view-point of origin. This, as already noted, is *Geomorphology* in its proper sense, though it is more commonly known by the name

of *Physiography*, which formerly had a very different meaning. Finally there is the study of the changes in the earth's surface, or its geography through the successive ages of the earth's history, — together with the changes in climate and the dispersions and migrations of the organisms and the causes which effected these. This is the latest of the several aspects of Historical Geology and is now termed *Palæogeography* or the geography of the past. In this field the palæogeography of the Pleistocene period has been most extensively studied, and a separate branch, that of *glacial geology*, has been developed. *Geography*, in the usual sense of the term, is the geography of the modern or Holocene period of the earth's history.

II. *Geology in its Relation to the Welfare of Man*

So far we have been considering geology in its pure science aspect, that which appeals to the inquiring mind of man in search after truth and knowledge, without ulterior motives of usefulness. There is, however, another aspect of our science, and one which in recent times has come strongly to the front. This is *applied geology*, in which geological facts and forces are viewed in their relation to the needs and requirements of man. As has already been intimated, the application of any science for any purpose whatsoever is successful in direct proportion to the profundity of knowledge possessed by the applier. No successful exploration of geological products or application of forces is possible without a thorough understanding of the facts and principles of the science, and the student who wishes to follow the applied side of his science should not fail to make his preparation in the pure science side as broad and as profound as circumstances will permit.

Among the earliest problems, to the solution of which geological knowledge has been applied, are those of mining. Indeed, the science of geology, in a measure, developed in response to the needs of the miner for accurate knowledge of the conditions of occurrence, distribution, and mode of origin of the valuable mineral deposits. To such an extent has this been carried, that a separate branch of *mining geology* has come into existence. Moreover, as our knowledge increased and the possibility of more detailed application of our science became apparent, special subdivisions of mining geology have been developed, and it is found that individuals can profitably

devote themselves to the cultivation of a narrow field, to the practical exclusion of the others. Thus there have been developed the branches of *coal geology*, of *petroleum* and *gas geology*, and of *salt geology*, including the geology of potash, phosphates, nitrates, borax, and other salts, and of bauxites and other aluminum ores. In these branches the investigator confines himself to the problems involved in the occurrence of these substances, which are chiefly restricted to the stratified rocks. It is now well recognized that successful search for such deposits can only be undertaken by one well versed in the science of stratigraphy (including index fossils) and structural geology, while a thorough understanding of the principles of physiography and palæogeography is almost indispensable. The mining geologist who devotes himself primarily to the problems of the metallic deposits must have not only a thorough knowledge of mineralogy, petrology, and structural geology, but of dynamic geology as well, and especially of the chemical and physical principles involved in ore deposition. As many ores are also found in stratified deposits, a knowledge of stratigraphy and of index fossils is necessary, while an understanding of the principles of physiography and palæogeography will also be found of value in many cases.

Geology, too, plays an indispensable rôle in the solution of many important engineering problems. In the construction of the Catskill aqueduct for New York City, a force of competent geologists was constantly employed, and specialists were frequently called upon for consultation. This same need was felt after the construction of the Panama Canal had been undertaken, and a resident geologist was appointed to supervise the later phases of construction. That many difficulties might have been avoided had such supervision existed from the outset of the undertaking, is now generally conceded.

Geological advice has always been employed in the construction of great tunnels such as those piercing mountains or passing under rivers and other water bodies. In many cases, too, the selection of sites for bridges, dams, and other great engineering works has been based on geological advice, while in other cases, where such advice has not been sought or has been disregarded, disastrous consequences have resulted. In consequence of the growing recognition of the need of geological study in the undertaking of engineering problems, the special branch of *engineering geology* has been

developed. The geological engineer must be primarily a structural geologist and one who has a thorough grasp of the principles of dynamic geology, including hydrology as well, while physiography too is of great importance to him. To a lesser degree a knowledge of rock types, of stratigraphic principles, and of index fossils will be needed by him, and not infrequently a knowledge of palæogeography, especially that phase which deals with the Pleistocene, or the problems of the glacial period, will be found of the greatest value.

Finally there has been developed in recent years the special branch of geology which deals with the problems involved in military campaigns, and to this the name *war* or *military geology* has been applied. Some of these problems are concerned with the proper location of sites for camps, and trenches, and with water supply and sanitation, and for these a knowledge of structural geology, of rock types, of stratigraphy, and of glacial geology has been found necessary. Other problems are of an engineering type and require the preparation of the geological engineer. Again, the problems involved in military operations need for their solution a well-trained physiographer and a competent meteorologist as well. Problems concerned with naval warfare require the attention of one well versed in hydrology, especially that phase of it which deals with the oceans, or oceanography.

There are other ways in which a knowledge of geology has become useful to man, and as the science itself is developed new channels of application into which it may be directed will no doubt be discovered.

III. *The History of Geology*

The student should further realize that the development of his science, the history of geologic thought, cannot be neglected by him. We profit by the mistakes of our predecessors as much as we do by their achievements, and the history of the discovery of facts and of the development of geological opinion since the days of the Greek philosophers is fraught with lessons equal in import to those gained from the pursuit of the history of any other department of human thought and endeavor. At this point it will be desirable for the student to read the masterly sketch of this history from the pen of Sir Archibald Geikie, the book entitled *Founders of Geology*, and if possible follow this by a perusal of the older

historical sketch by Sir Charles Lyell in volume I of his *Principles of Geology*. For greater details the student is finally referred to the *History of Geology and Palæontology* by Carl von Zittel, translated into English by Maria Ogilvie Gordon. The history of geology in America is adequately and fully treated by Dr. George P. Merrill in his book, *Contributions to the History of American Geology*.

CHAPTER III

METHODS OF APPROACH IN THE STUDY OF THE EARTH

The Rise of Geological Observation and Interpretation

The geologist is, above all things, an observer in the great out-of-door world. The man whose horizon is bounded by the walls of a city can never be a geologist, though he may gain much scientific knowledge from books and from an inspection of collections in museums and laboratories. The true geologist, however, goes directly to the earth and there begins his inquiries. Not until observations of natural facts and phenomena were made *in extenso* was the inquiry of the philosophers regarding the earth and its history placed on a scientific basis. Scattered observations and more or less accurate deductions were made even in antiquity. Thus Aristotle, in the third century B.C., had a very considerable understanding of the work of rivers and reasoned correctly regarding the changes in the land and sea at former times. The painter Leonardo da Vinci (1452–1519) correctly reasoned, from an observation of the fossils found in the foothills of the Apennine Mountains, that they were the shells of once living animals, though they were generally regarded either as freaks of nature (*lusus naturæ*) or as modern shells dropped by the pilgrims in their voyages across these mountains. It is true that the significance of fossil sea shells was recognized by the Greek philosophers but their explanations

Fig. 6. — Georges Léopold Chrétien Frédéric Dagobert Cuvier.

were generally ridiculed during the Middle Ages. It was, however, not until the latter part of the eighteenth and the early part of the nineteenth century that systematic investigations of the rocks of the earth and their contained fossils began, and from this period we date the birth of geology as a science. Scientific geology arose more or less simultaneously in the different countries of Europe. In France Etienne Guettard (1715–1786) and Nicholas Desmarest (1725–1815) were among the first to bring observation of facts to the fore, while Buffon (1707–1788) indulged in brilliant speculations on the origin of the earth. Later Alexander Brongniart (1770–1847) investigated the rocks around Paris, and Georges Cuvier (1769–1832, portrait, Fig. 6) and the Chevalier de Lamarck (1744–1829, portrait, Fig. 7) described their fossils. In Germany Abraham Gottlob Werner (1750–1817, portrait, Fig. 8), who is often called the founder of German geology and who was Professor at the Mining School at Freiberg i. S., exerted a profound influence on geology especially by his teachings, to which men flocked from all countries. Being mostly an observer of the details of specimens and rarely venturing beyond his immediate surroundings for field observations, many of his geological deductions have proved erroneous — though his pupils and followers, notably Leopold von Buch, extended their observations over wide areas and added much to the store of geological facts as well as to its philosophy. Switzerland had its enthusiastic

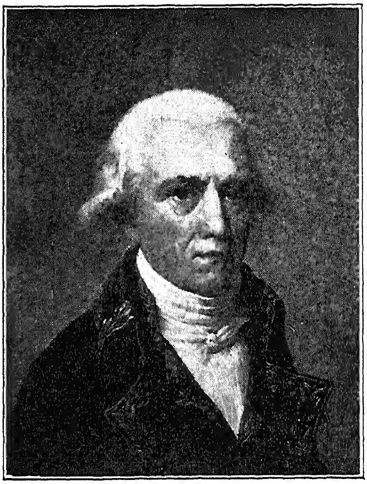


Fig. 7. — Jean Baptiste Pierre Antoine de Monet de Lamarck.

Fig. 8. — Abraham Gottlob Werner.

student of the structure and history of the Alps in the person of H. B. de Saussure (1740–1799), and Russia had in Pierre Simon Pallas (1741–1811) its careful student of the Ural Mountains, and the rocks outcropping there and elsewhere in the empire. In Great Britain many men contributed to the discovery of facts and the interpretation of these. Among them the first rank is given to James Hutton (1726–1797, Fig. 9), whose work marks a turning point in the history of geology, for he insisted that "the past history of the globe must be explained by what can be seen happening now, or to have happened only recently,"[1] a dictum which has since become the very cornerstone of geology.

Fig. 9. — James Hutton, M.D.

Hutton's great work, *Theory of the Earth with Proofs and Illustrations*, is better known through the classic volume, *Illustrations of the Huttonian Theory*, by his friend John Playfair (1802, Fig. 10), which no student of geology should neglect to read. In this work are contained many of the fundamental principles with which geologists are concerned to-day, and they are illustrated by a wealth of facts gleaned by Hutton from his rambles through Scotland and other countries.

Fig. 10. — John Playfair.

Another of the Scottish founders of geology was Sir James Hall, to whom we owe the origination of experimental geology. The best known, however, among the early English geologists was William Smith (1769–1839, portrait, Fig. 11), who is generally called the "Father of English Geology." He determined not only the correct

[1] Geikie, *Founders of Geology*, p. 299.

successions of the English rock formations, and made the first geological map of England, but gave to many of the formations the names which they bear to-day.

Fig. 11. — William Smith.

Finally, the student should remember among English geologists the name of Sir Charles Lyell (1797–1875, portrait, Fig. 12), as that of a man who has had the most profound influence on geological thought. His great work, the *Principles of Geology*, has become a classic of geological literature.

Among the men who exerted a profound influence on American geology in the early days of its development, the names of William McClure (portrait, Fig. 13) and Amos Eaton (portrait, Fig. 14) stand out prominently. McClure, born in Scotland in 1763, became an American citizen near the close of the century. In 1809 he published the first important work on American Geology, in which appeared the first geological map of the Eastern United States, and one of the first geological maps of the country. Amos Eaton (1776–1842, Fig. 14), born in New York state, is known especially for his *Index to the Geology of the Northern States* (1818), which was the first geological textbook published in America, and in this and subsequent works he laid the foundation for the New York geological system. Many of the names of American formations still current were first applied by him. He also made the first geological map of New York. The important influence which McClure and Eaton had

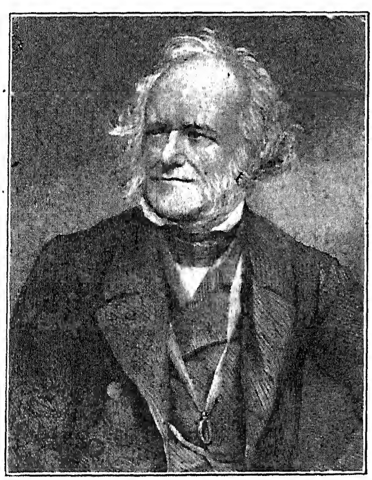


Fig. 12. — Sir Charles Lyell.

on the development of American geology has been recognized by the designation of the first two eras in the history of this science in America as the Maclurean (1785–1819) and the Eatonian (1820–1829) (Merrill). Other early American geologists will be referred to in later chapters.

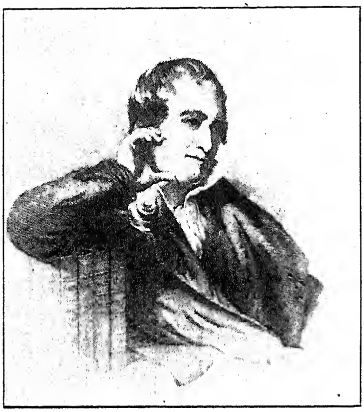


FIG. 13. — William McClure.

THE FIELD OF GEOLOGICAL OBSERVATIONS

"Where, then," the student will ask, "can the facts of geology be observed, and how have they become available?" To get at the facts of structural geology the student must go to the rocks. True, the rocks and the minerals and the fossils are brought to him in museums and laboratories, and he will do well to begin his studies of selected examples thus brought together and capable of being examined under the most favorable conditions. But the knowledge thus gained must be amplified and correlated by repeated visits to the home of the rocks, where alone their larger relations and their true significance in the history of the earth can be ascertained.

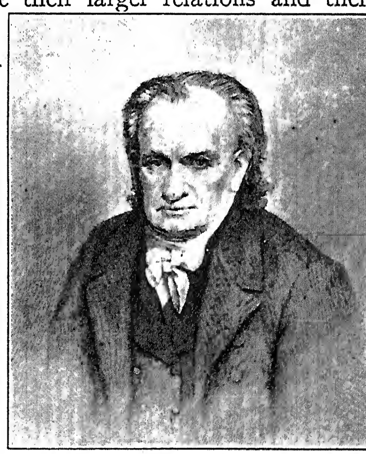


FIG. 14. — Amos Eaton.

The Field for the Study of Rocks and Rock Structures

Rock Exposures in Flat Countries. — The dwellers in the interior of our country, or the traveler on the broad plains of northern Germany, of Russia, of Hungary, or of China, will find little opportunity to get a view of the rocks which underlie these regions, for an almost continuous mantle of soil and drift covers the solid rock. Only where rivers have cut channels through the surface layer of loose material, the *mantle-*

rock, or where quarries have been opened, or construction operations have necessitated excavation down to and into the solid bed rock, is there an opportunity for observation of the rocks beneath the mantle-rock. River valleys and gorges are therefore the favorite resorts of the geologist of the plains, while quarries, railroad cuts, and other excavations which expose the rock, likewise receive his attention. Borings and drillings for oil, gas, or water often prove of use to him, though generally, except where the diamond drill is used, and the core preserved, the record of such borings is only of doubtful and minor value. Salt shafts, such as those in central New York and that near Detroit, Mich., furnish excellent sections at the time of excavation. Fortunately for the geologist of the plains, however, few regions of any great extent are wholly covered by mantle-rock; more commonly low-lying ridges of rock, formed by resistant layers, are exposed above the general surface of the soil and drift mantle. Such "ledges" generally mark the edges of beds of hard rock which have a gentle slope away from the edge of the ledge. When the ledge-forming layer is very thick, a cliff of some height may result, and this generally furnishes abundant opportunity for observation and deduction.

All natural exposures of the rock are called *outcrops*, and the outcropping ledges together with the exposures in the stream channels, especially those which cut across the cliffs, furnish to the geologist of the flat countries his most satisfactory data. We may note a few examples.

Illustration from New York State. — The state of New York furnishes an illustration of the types of rock outcrop in ledges referred to in the preceding paragraphs. Over the greater part of the state the rocks are so gently inclined that they appear horizontal to the eye, and it is only when they are seen in the cliffs of Niagara gorge and along Lake Erie that their gentle southward descent becomes noticeable. Such a section, considerably generalized, is shown in the following diagram (Fig. 15).[1] Where the beds end in the air upon the north, the harder ones, such as limestones and sandstones, form a series of low cliffs, while the ends of the softer shale beds are usually marked by broad flat-bottomed valleys. The

[1] The usual method of drawing sections is to place the north end upon the right, but this is here reversed, because the observer along Lake Erie views the cliffs from the west, and therefore south is on his right.

largest and deepest of these valleys is occupied by Lake Ontario, while others are filled by soil which conceals the rock. These cliffs or escarpments generally have an abrupt northern face across the edge of the hard rock, and in these faces quarries are generally opened.

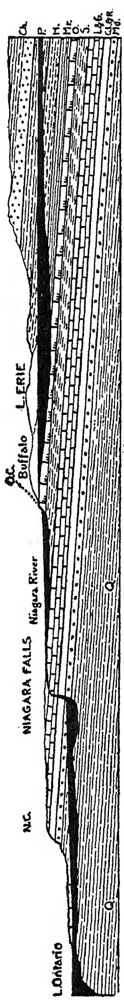


FIG. 15. — Section across Western New York, showing the rock formations exposed on the Niagara River and on the shores of Lake Erie. *Q*, Queenston shales; *Md.*, Medina; *Cl. & R.*, Clinton formation and Rochester shale; *L. & G.*, Lockport and Guelph dolomites; *S.*, Salina shales, etc.; *O.*, Onondaga limestone; *Mr.*, Marcellus shale; *H.*, Hamilton shale; *P.*, Portage beds; *Ch.*, Chemung sandstone and shales; *N. C.*, Niagara cuesta; *O. C.*, Onondaga cuesta.

These cliffs can be traced with more or less interruption across New York state from the Niagara River and Lake Erie (Fig. 16) to the Hudson, although they become modified because some of the beds seen in the western part of the state die out, or change in character and new ones appear (Fig. 17). This is shown on the geological map of the state of New York, where a series of broad color bands extends east and west across the state. Each color band in general represents one rock layer or group of layers, and the width of the color band indicates the amount of exposure of each which would appear were all the covering soil and vegetation removed; or in other words, the amount by which each lower bed projects beyond the next higher one which covers it.

Wherever streams have cut across this series of beds, gorges are formed, in the walls of which the cut edges of the rocks, the soft layers as well as the hard ones, are shown. The most striking examples of such gorges are shown along the Genesee River, which crosses the state from south to north. In the section from Rochester northward it cuts the lower beds, the harder strata producing waterfalls. In the section between Portage and Mt. Morris, it cuts the higher strata, and here too several waterfalls are formed by hard layers. Between these two points many smaller tributary streams have cut into the sides of the valley and exposed the rocks. Here, too, are situated several deep shafts which go

down vertically to the Salina salt beds and during the cutting of which the succession of the rocky beds was ascertained.

A good understanding of the succession of this series of rocky formations is obtained by the traveler who passes from the Adirondack Mountains southwestward across the state to Elmira, especially if he take advantage of the various sections exposed in the gorges of the streams and the banks of the Finger Lakes.

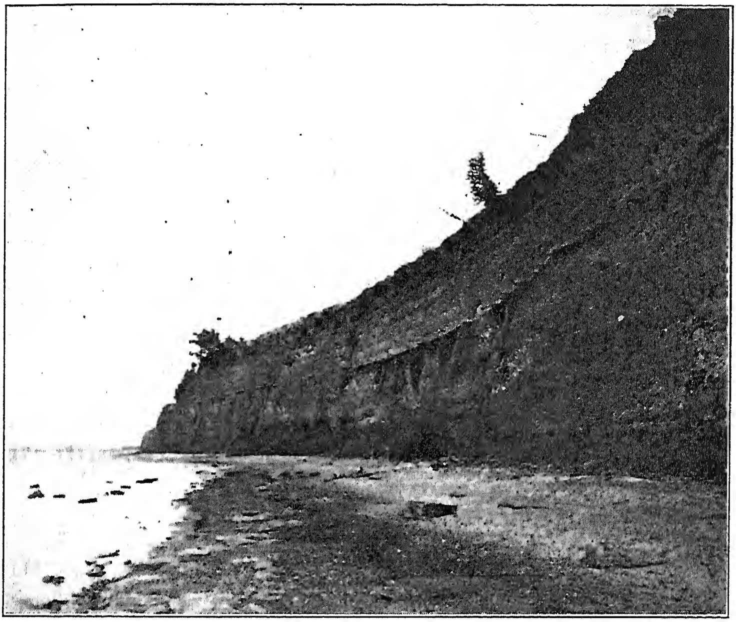


FIG. 16. — Cliff of Devonian rocks exposed on the shores of Lake Erie, south of Buffalo. Typical of rock exposures shown on the lake shore from Buffalo to Cleveland. (The section shows Hamilton (Wanakah) shales at the base, the projecting Morse Creek limestone, above which lie the Windom shales and higher Devonian shales.)

It was by the study of these natural outcrops of the state, supplemented by those made on the sections exposed during the cutting of the Erie Canal in 1817–1825, that the foundation of American geology was laid by such men as Amos Eaton, and by James Hall and others associated with him on the geological survey of New York state.

Other Exposure of this Type. — The type of outcrop just described is found in most regions of flat-lying rocks in our own country as

well as abroad. Thus the geologist who starts from Baraboo, Wisconsin, and proceeds southeastward to Lake Michigan at Milwaukee, will cross such a series of rocky ridges separated by soil-filled valleys, and a similar experience awaits the traveler across Kansas from southeast to northwest, or the one who proceeds southward across Oklahoma, or journeys from central Texas either northwestward or southeastward. The traveler across England from Liverpool to London also crosses such a series of rocky ridges, which

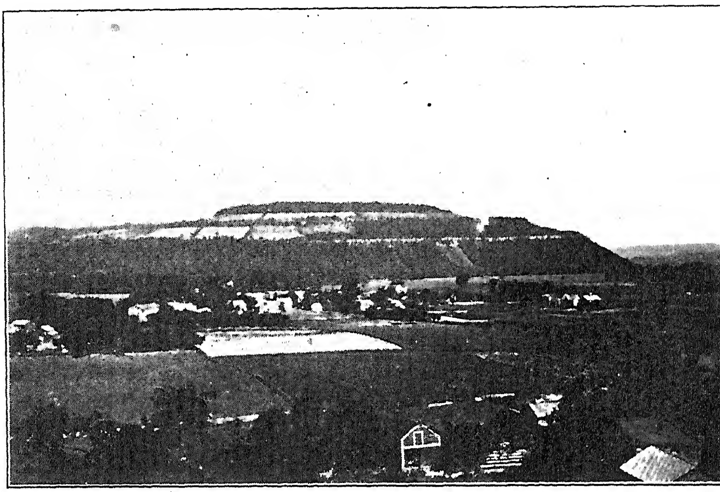


Fig. 17. — View of West Hill, Schoharie, a terraced edge of the Helderberg escarpment or cuesta, in eastern New York. Note the prominent cliffs formed by the limestone members and the intermediate slopes formed by softer beds. (Courtesy of N. Y. State Geological Survey.)

in general extend in a northeast-southwest direction, and are formed by a succession of nearly horizontal rock-layers with westward facing cliffs, though these are not generally visible from the train. Similar outcrops of nearly horizontal layers of rock surround Paris in constantly widening circles on three sides. The edges of some of these rocks form cliffs or escarpments facing outward. If one were to represent the rock formations which underlie Paris, and which have a shallow basin-like structure, by a nest of plates, the smallest at the top, the successive rims of these plates would represent the encircling cliffs, while the location of Paris would be in the center of the uppermost and smallest plate. Many rivers have cut channels through the edges of these rock plates, while others

flow in the depressions between successive rims. Thus numerous and excellent exposures of the rocks are found, even though the marginal portions between the edges of successive rock layers are frequently covered by soil and vegetation. These numerous rock exposures made possible the observations which gave the French founders of our science the data on which to build their deductions, and the cliffs which they form around Paris were of the utmost importance in the conduct of the Great War so recently closed.

Outcrops in Mountainous Countries. — It is, however, in the elevated portions of the earth — the mountains and chains of uplands — that rock outcrops are most frequent on the surface of the land. Here the soil and rock débris lodges only in the depressions, while between these the ledges protrude and give opportunities for observation. Here, too, deep cañons are cut by the rivers and glaciers and thus additional rock-walls are opened for observation. German, Austrian, and Swiss geologists have for the most part been limited to such regions for their observations, and the wonderful rock exposures of the Alps and other mountains have made it possible for them to carry their studies along certain lines to great lengths. Werner, the father of German geology, made most of his observations in the subdued[1] mountain district of Saxony, especially the Erzgebirge, which has long been famous for its old and extensive mining operations.

Since France and Italy also border on the Alps, and have mountain ranges of their own, the geologists of these countries were enabled to avail themselves of the rocks and rock structures thus revealed. British geologists, too, have been able to some extent to resort to this type of exposure, though in these moisture-enveloped islands, as over parts of Scandinavia as well, the dense though low cover of vegetation and the peat accumulations obstruct much of the underlying rock, as all students of Irish geology know only too well. The Highlands of Scotland, however, furnish many good opportunities for observation, as do also many of the higher English districts and especially the mountain region of Wales. Swedish geologists have frequently had to resort to digging through the surface layers to get at the underlying rock, and it is not an uncommon sight to see the Swedish geologist in the southern interior accompanied by a factotum, whose duty it is to wield pick and shovel.

[1] This term implies that the old mountains have been much worn down.

In European Russia and adjoining districts there are vast areas of flat-lying rocks covered by soil and drift, so that, except along the coast and in the river channels, outcrops of the bedrock are difficult to find. But where these rocks are uplifted — in the Ural Mountains on the east, the Caucasus on the south, and the Carpathians on the west — outcrops abound, and here the true relationships of the rock formations may be ascertained.

In America, the New England uplands, the White, Green, and Adirondack Mountains, and the Appalachian Chain furnish an

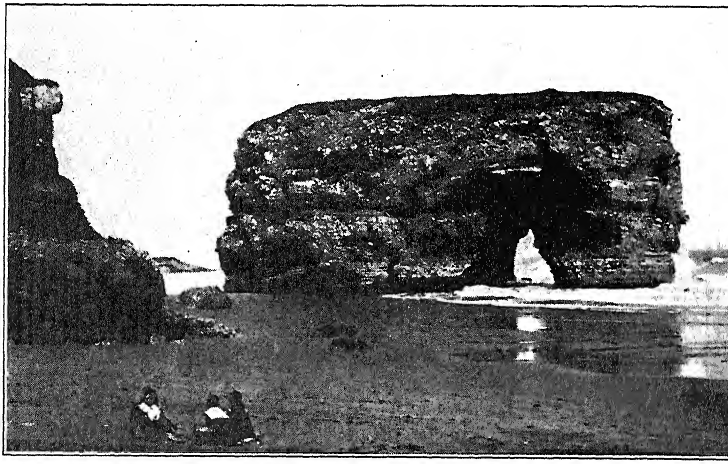


FIG. 18. — Marsten Rock: View on the North Sea coast of England (Durham), showing characteristic erosion features in a detached mass of Magnesian Limestone of Permian age, which was formerly united with the cliff on the left. This is typical of the rocky character of much of the British coast, though the kind of rock, the structures, and the erosion forms vary from point to point.

abundant series of rock outcrops for the eastern geologist. The old and generally much-subdued mountain system, the rocks of which may be traced by frequent outcrops from New York City to the Highlands of the Hudson, and which can be followed southwestward through New Jersey, Pennsylvania, and Maryland, and indeed all the way down to the Carolinas, where it constitutes the older Appalachian Chain, is a typical example of an elevated, though for the most part not very mountainous, country, and here outcrops abound. Many of our western mountains are especially well adapted for geological observation, for here the aridity of the climate prevents the growth of much vegetation, and the rock structures,

frequently developed on a gigantic scale, are visible for many miles. This makes the Rocky Mountains a veritable paradise for the American geologist.

Outcrops upon the Coast. — Of all the natural rock exposures, however, those of the coast-line are the most attractive, and in many respects the most satisfying. Wherever the sea-coast or the shore of a large lake is formed by rocks which rise above the surface of the water, the cutting work of the waves keeps the exposure fresh. A tramp along a rocky sea-coast is replete with interest to the geologist, and many of the choicest bits of geological observation have been made on such sea-cliffs. Great Britain, with its wonderful rocky sea-coast, probably leads the world in the variety and significance of rocks and rock structures there exposed (Fig. 18).[1] No student of geology can afford to neglect the wonderful English and Scottish coast, which has furnished the British geologists so many opportunities for the observation of facts that there, more than elsewhere, geological science has advanced, since the days of William Smith, with phenomenal strides. This is probably the reason why English geology quickly became the standard of comparison for other nations, in whose home countries observation was a more arduous task, because they did not include such marvelous coast exposures.

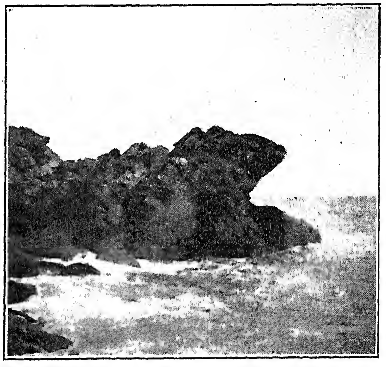


FIG. 19.—Pulpit Rock, Nahant (Mass.). One of the most picturesque and instructive rock sections upon the Atlantic coast of New England. The rocks are metamorphosed Cambrian shales and limestones with a great diabase sheet (sill) intruded between the strata, and the whole eroded by the waves working chiefly upon the softer strata. (Photo by A. W. G.)

Northern France, too, has a coast-line of great interest to the geologist, and so has Norway. The coast-line of Germany, on the other hand, is mostly sandy, and there is little diversity in the types of the facts which it discloses.

The Atlantic coast-line of North America is for the most part a sandy one. Only in New England, in the Canadian coastal prov-

[1] See also Figs. 113, 114, 120, 121, 203, 498, 510, 511, 530–532, 719–721, 723 a, b.

inces, and in Newfoundland can be seen coastal sections comparable to some extent to those of Great Britain. The northern regions, however, are accessible with difficulty, and have only recently been investigated. But the New England coast, and especially that of Massachusetts (Fig. 19), is a Mecca for American geologists, and many of the workers in American geology have had their preliminary training through a study of that interesting region.

Regions for the Study of Dynamic Geology

Although the principles of dynamic geology, the workings of the chemical and physical forces, may be studied to much advantage in the laboratory — such study, too, is incomplete without recourse to the outdoor field. It is upon the sea-shore that some of the profoundest lessons of erosion by waves, of transportation by currents, and of deposition in quieter waters can be learned. Here, too, the method of entombment of fossils and the formation of many original structures, such as ripple-marks and the like, can be observed. Rocky as well as sandy and muddy shores should be visited. Shores of large lakes may serve as a substitute in inland regions, but lakes have in addition many characters of their own. Ponds and temporary pools also teach their lessons. River valleys and gorges, rapids and waterfalls, brooks, and even the roadside gutter, furnish lessons in dynamic geology, as do also the hillside, the mountain slopes, and the elevated peaks, where rocks are shattered by frost, and decay under atmospheric influence. Glaciers present many illustrations of dynamic geology, while caverns and underground channels have special lessons to teach. The deserts and all regions where wind is at work furnish illustrations of the mechanical activities of the wind, while pools and salt pans in arid regions furnish illustrations of chemical activities and of precipitation of salts through condensation of the water under evaporation. Springs, too, illustrate dynamical activities, both physical and chemical, and artesian wells, oil wells, geysers, and similar phenomena are replete with them. Finally, volcanoes and other such phenomena furnish the means for the study of igneous activities.

The great English geologist, Sir Charles Lyell, whom we sometimes call the "Father of Modern Geology," has said that the geologist must be primarily a traveler — he must go to other lands than his own and so widen the scope of his experience. Werner,

the founder of German geology, confined his observations mainly to his limited Saxon district, and attempted to formulate from these observations laws which should govern the rest of the world. Naturally he fell into many and profound errors, so that to-day scarcely one of his theories is held. Since his day German geologists have, however, become great travelers, not only in their own but in most other lands. As a result, their observations have become of wide scope, and they have added much to geological knowledge. British and American geologists have only recently begun to follow the advice of Lyell, but already their efforts have been crowned with considerable success.

Let the student of geology, then, come to realize that the value of his deductions increases in proportion to the range of his observations, and that no single country or region of the world will give him all he needs. The American student, owing to the wide extent and diversity of his country, is perhaps more favored in this respect than is the geologist of any other nationality, but at present only a limited portion of our country has become sufficiently accessible to make extended observations possible.

The Importance of Geological Literature

Finally, it must not be overlooked that the observations of our predecessors are recorded in the literature of the science, and that here we find a mine of information, the value of which cannot be overestimated. No one can repeat all of the observations which have been made in the past, even were such repetition desirable. In addition to the laboratory and field, then, the student of geology must go to the library, and a thorough understanding of the literature on his special field is of fundamental importance to the worker. Besides special books on different aspects of the science, the student should gain familiarity in the use of the official publications issued by the governments of the various countries, the proceedings of scientific societies, and the special journals devoted to geology and kindred sciences.

CHAPTER IV

MATERIAL OF THE EARTH'S CRUST

THE material of which the crust of the earth consists is spoken of as *rock*, a term which we shall presently define more precisely. Rocks are in turn combinations of *minerals* or large aggregates of a single material, and these are formed by the combination of *chemical elements*, or by the union of those elementary combinations of elements which are called *ions*. The study of chemical elements and of their combination into ions and the union of these to form other substances (salts, etc.), belongs in the domain of chemistry. The study of minerals, their properties and occurrence, belongs to the special branch of the earth science called mineralogy. An elementary preparation in chemistry and mineralogy is necessary to the student, and should be obtained by him if possible before undertaking the study of geology. In this book we can give only a brief summary of the more important elements and minerals with which the student should have some acquaintance. The important minerals which enter into the composition of the rocks, or which themselves occur in rock-like masses, will be dealt with somewhat more fully in the discussion of these rocks.

THE CHEMICAL ELEMENTS AND THEIR PRIMARY COMBINATIONS

Of all the chemical elements which enter into the composition of the earth's crust, only a comparatively small number are of importance in combining to form the more common minerals and rocks. The principal ones are given in the following list from F. W. Clarke, in which their relative importance is also indicated.

Some of these elements occur pure in nature and are then called native elements. Among these are oxygen, nitrogen, sulphur, carbon, and the metals gold, silver, copper, platinum, etc. The majority of elements, however, form combinations among themselves, with the result that more or less stable compounds are produced.

The More Important Elements and Their Distribution

Name of Element	Symbol	Lithosphere 93 Per Cent of Whole	Hydrosphere 7 Per Cent of Whole	Average Including Atmosphere
Oxygen	O	47.33	85.79	50.02
Silicon	Si	27.74	—	25.80
Aluminum	Al	7.85	—	7.30
Iron	Fe	4.50	—	4.18
Calcium	Ca	3.47	.05	3.22
Magnesium	Mg	2.24	.14	2.08
Sodium	Na	2.46	1.14	2.36
Potassium	K	2.46	.04	2.28
Hydrogen	H	.22	10.67	.95
Titanium	Ti	.46	—	.43
Carbon	C	.19	.002	.18
Chlorine	Cl	.06	2.07	.20
Bromine	Br	—	.008	—
Phosphorus	P	.12	—	.11
Sulphur	S	.12	.09	.11
Barium	Ba	.08	—	.08
Manganese	Mn	.08	—	.08
Strontium	Sr	.02	—	.02
Nitrogen	N	—	—	.03
Fluorine	Fl	.10	—	.10
All other Elements including Gold, Silver, Platinum, Arsenic, Copper, Lead, Mercury, Nickel, Tin, Zinc, Radium, etc.	—	.50	—	.47
Total		100.00	100.00	100.00

Chemical Combinations

The following types of chemical combinations exist in nature or are produced in the laboratory.

Oxides. — Combination of an element with oxygen. Examples: Silica (SiO_2); Carbon dioxide (CO_2); Iron oxide (Fe_2O_3); Water (H_2O).

In the first of these, two parts of oxygen unite with one of silicon to form silica or quartz; in the second, two parts of oxygen in like manner unite with one of carbon to form the gas carbon dioxide. In the third example, three parts of oxygen unite with two of iron to form the sesquioxide of iron; and in the fourth example one part of oxygen unites with two of hydrogen to form water.

Hydroxides. — These are combinations of an element (metal) or a group of elements with oxygen and hydrogen, the last two in equal parts. Examples: Sodium hydroxide or caustic soda ($NaOH$); Potassium hydroxide or caustic potash (KOH); Aluminum hydroxide (the mineral Gibbsite, $Al(OH)_3$). In this last example it requires three parts of the (OH) group to satisfy the combining power of one part of aluminum.

Oxyhydroxides. — Like the preceding, but with an additional molecule of oxygen.[1] Examples: Aluminum oxyhydroxide, the mineral diaspore ($AlO(OH)$); Iron oxyhydroxide or goethite ($FeO(OH)$). Both hydroxides and oxyhydroxides may also be expressed as combinations of oxides and water (H_2O); thus:

$$2\left\{\begin{matrix} Al(OH)_3 \\ \text{Aluminum} \\ \text{hydroxide} \end{matrix}\right\} = \left\{\begin{matrix} Al_2O_3 \\ \text{Aluminum} \\ \text{oxide} \end{matrix}\right\} + 3\left\{\begin{matrix} H_2O \\ \text{Water} \end{matrix}\right. \qquad \text{(Gibbsite)}$$

$$2\left\{\begin{matrix} AlO(OH) \\ \text{Aluminum} \\ \text{oxyhydroxide} \end{matrix}\right\} = \left\{\begin{matrix} Al_2O_3 \\ \text{Aluminum} \\ \text{oxide} \end{matrix}\right\} + \left\{\begin{matrix} H_2O \\ \text{Water} \end{matrix}\right. \qquad \text{(Diaspore)}$$

$$\left.\begin{matrix} FeO(OH) \\ \text{Iron oxy-} \\ \text{hydroxide} \end{matrix}\right\} = \left\{\begin{matrix} Fe_2O_3 \\ \text{Iron} \\ \text{oxide} \end{matrix}\right\} + \left\{\begin{matrix} H_2O \\ \text{Water} \end{matrix}\right. \qquad \text{(Goethite)}$$

The hydroxides and oxyhydroxides also form *bases* with which *acids* combine to form *salts*.

Acids. — These are combinations of certain elements such as chlorine, carbon, sulphur, silicon, etc., which are called negative elements, or their oxides (negative ions), with hydrogen or with the oxyhydrogen (OH) combination or *radical*. Examples: Hydrochloric acid HCl, (Hydrogen chloride + water); Carbonic acid, $H_2CO_3 = CO + 2(OH)$; Sulphuric acid, $H_2SO_4 = SO_2 + 2(OH)$.

Salts. — A compound formed by the reaction between an acid and a base (hydroxide or oxyhydroxide) with the simultaneous formation of water, is called a salt.

Thus:

$$\left.\begin{matrix} Na(OH) \\ \text{Sodium} \\ \text{hydroxide} \end{matrix}\right\} + \left\{\begin{matrix} HCl \\ \text{Hydrochloric} \\ \text{acid} \end{matrix}\right\} = \left\{\begin{matrix} NaCl \\ \text{Sodium chloride} \\ \text{or common salt} \end{matrix}\right\} + \left\{\begin{matrix} H_2O \\ \text{Water} \end{matrix}\right.$$

$$\left.\begin{matrix} Ca(OH)_2 \\ \text{Calcium} \\ \text{hydroxide} \end{matrix}\right\} + \left\{\begin{matrix} H_2SO_4 \\ \text{Sulphuric} \\ \text{acid} \end{matrix}\right\} = \left\{\begin{matrix} CaSO_4 \\ \text{Calcium} \\ \text{sulphate} \end{matrix}\right\} + \left\{\begin{matrix} 2H_2O \\ \text{Water} \end{matrix}\right.$$

[1] More correctly derived from the hydroxide by the abstraction of water, as shown on comparison of the formulas of Diaspore and Gibbsite, the former having two molecules of water less.

New salts may also be formed by the reaction, in solution, of a strong acid upon a salt with a weak acid, when the weaker acid is set free.
Thus:

$$\left.\begin{array}{c} SrCl_2 \\ \text{Strontium} \\ \text{chloride} \end{array}\right\} + \left\{\begin{array}{c} H_2SO_4 \\ \text{Sulphuric} \\ \text{acid} \end{array}\right\} = \left\{\begin{array}{c} SrSO_4 \\ \text{Strontium} \\ \text{sulphate} \end{array}\right\} + \left\{\begin{array}{c} 2HCl \\ \text{Hydrochloric} \\ \text{acid} \end{array}\right.$$

Or they may be formed by the interaction of two salts in solution to form a less soluble salt.
Thus:

$$\left.\begin{array}{c} BaCl_2 \\ \text{Barium} \\ \text{chloride} \end{array}\right\} + \left\{\begin{array}{c} Na_2SO_4 \\ \text{Sodium} \\ \text{sulphate} \end{array}\right\} = \left\{\begin{array}{c} BaSO_4 \\ \text{Barium} \\ \text{sulphate} \end{array}\right\} + \left\{\begin{array}{c} 2NaCl \\ \text{Sodium} \\ \text{chloride} \end{array}\right.$$

The barium sulphate is insoluble and will be precipitated out.

Ions. — When certain chemical compounds such as acids, salts and the bases, are dissolved in water, they are believed to be dissociated into two or more parts which are either the elements or their simple combinations, and which are called *ions.* They exhibit a marked behavior towards the passage of an electric current through the solution; some, regarded as charged with positive electricity, being attracted by the negative electrode, and others, regarded as negatively charged, being attracted to the positive electrode. Examples are:

$$\text{Acids}\left\{\begin{array}{lll} HCL = \overset{+}{H} \text{ positive and} & \overset{-}{Cl} \text{ . . . .} & \text{negative ions} \\ H_2SO_4 = \overset{+}{H_2} \text{ positive and} & \overset{-}{SO_4}{}^{1} \text{ . . .} & \text{negative ions} \end{array}\right.$$

$$\text{Base}\quad KOH = \overset{+}{K} \text{ positive and} \quad \overset{-}{(OH)} \text{ . . .} \quad \text{negative ions}$$

$$\text{Salts}\left\{\begin{array}{lll} NaCl = \overset{+}{Na} \text{ positive and} & \overset{-}{Cl} \text{ . . . .} & \text{negative ions} \\ CaSO_4 = \overset{+}{Ca} \text{ positive and} & \overset{-}{SO_4} \text{ . . .} & \text{negative ions} \end{array}\right.$$

[1] In dibasic acids the dissociation takes place in two stages. In fairly concentrated solutions sulphuric acid dissociates wholly or in part as a monobasic acid. Thus: $H_2SO_4 = \overset{+}{H} + \overset{-}{HSO_4}$. The second stage takes place when the solution is more dilute. Thus: $\overset{-}{HSO_4} = \overset{+}{H} + \overset{=}{SO_4}$. (Jones, H. C., *The Nature of Solutions.*)

Minerals

All native elements, oxides, hydroxides, oxyhydroxides, acids, and salts which occur in nature in a solid state, are called minerals. They occur either in crystalline or uncrystalline (amorphous) form or both. Acids are rare as minerals, but native elements and oxides are common, while hydroxides and oxyhydroxides are not infrequently met with. By far the larger number of minerals, however, belong to the category of salts, among which the dominant ones are the silicates formed by the combinations of metals, etc., with silicic acid. The determination of minerals depends upon the recognition of their physical characters as well as of their chemical composition. There are many physical characters of which the more important ones will be briefly summarized.

Crystalline Form

Most minerals assume definite forms in which certain planes appear, which are found to have a definite relation to certain imaginary lines or crystallographic axes (coördinate axes) about which the crystal may be supposed to be built up. There are six systems recognized, based on the relative length and relationship of the axes. In the systems with three axes, these axes may differ in length, when they are designated by the letters a, b, and c, respectively, the c axis being the vertical one. If a and b are equal both are designated by the letter a; if all three are equal they are all called a. The various faces of the crystal are read with reference to the points at which they intersect the axis or would do so if both were extended.

If, in a simple crystal of one set of planes, a plane intersects all three axes (unit length), these axes being unequal, this plane is given the symbol $a:b:c$ (pyramid). If the two horizontal axes are equal, it is designated $a:a:c$ (tetragonal pyramid); if all three axes are equal, it is designated $a:a:a$ (octahedron). If the plane cuts two axes and is parallel to the third, this parallelism is indicated by the infinity sign (∞) and the formula becomes $a:b:\infty c$ (prism); $a:a:\infty c$ (prism) or $a:a:\infty a$ (dodecahedron) as the case may be; if it cuts only one axis and is parallel to the other two the designation is $a:\infty b:\infty c$ or $\infty a:b:\infty c$ (pinacoids); $\infty a:\infty b:c$ (basal pinacoids); $a:\infty a:\infty c$ (second order

prism); $\infty a : \infty a : c$ (basal plane) or $a : \infty a : \infty a$ (cube) according to the relative lengths of the axes. Planes cutting all three axes at the unit length are called *pyramid planes;* those that cut the two horizontal axes at the unit length and are parallel to the vertical one, are called *prism planes,* while those that cut only one of the horizontal axes, being parallel to the other and to the vertical one, are called *pinacoidal planes* except in the case where the two horizontal axes are of equal length (tetragonal system), when they are called prism planes of the second order. Those which cut the c axis and are parallel to the others are called *basal pinacoids.*

Finally, planes parallel to one horizontal axis and cutting the other and the vertical one are called *dome planes,* except in the case where the two horizontal axes are equal (tetragonal), when they are called pyramid planes of the second order. Other planes may occur which do not cut the axes at the unit length. These are designated by the coefficient m for the first variation from the unit length and n for the second. Thus with three equal axes we may have planes with the formula $a : a : ma$ (trigonal trisoctahedron), or $a : ma : ma$ (tetragonal trisoctahedron); or finally, $a : na : ma$ (hexoctahedron). The system with four axes has the three horizontal ones equal and at angles of 60° with one another, while the vertical one is at right angles to the others.

The Six Systems of Crystallization

I. Isometric. — Three axes of equal length or interchangeable and at right angles to one another. Fundamental forms: *cube* ($a : \infty a : \infty a$); octahedron ($a : a : a$); etc. (Fig. 20).

II. Tetragonal. — Two horizontal axes equal and interchangeable, the vertical one (c) of different length. All at right angles to one another. Fundamental forms: tetragonal prism[1] ($a : a : \infty c$); tetragonal pyramid ($a : a : c$); etc. (Fig. 21).

III. Hexagonal. — Three equal horizontal or interchangeable axes, forming angles of 60 degrees; a vertical axis of different length at right angles to the horizontal ones. Fundamental forms: hexagonal prism ($a : a : \infty a : \infty c$); hexagonal pyramid ($a : a : \infty a : c$); etc. (Fig. 22).

[1] All the prisms require, of course, basal planes or pyramids to complete the solid.

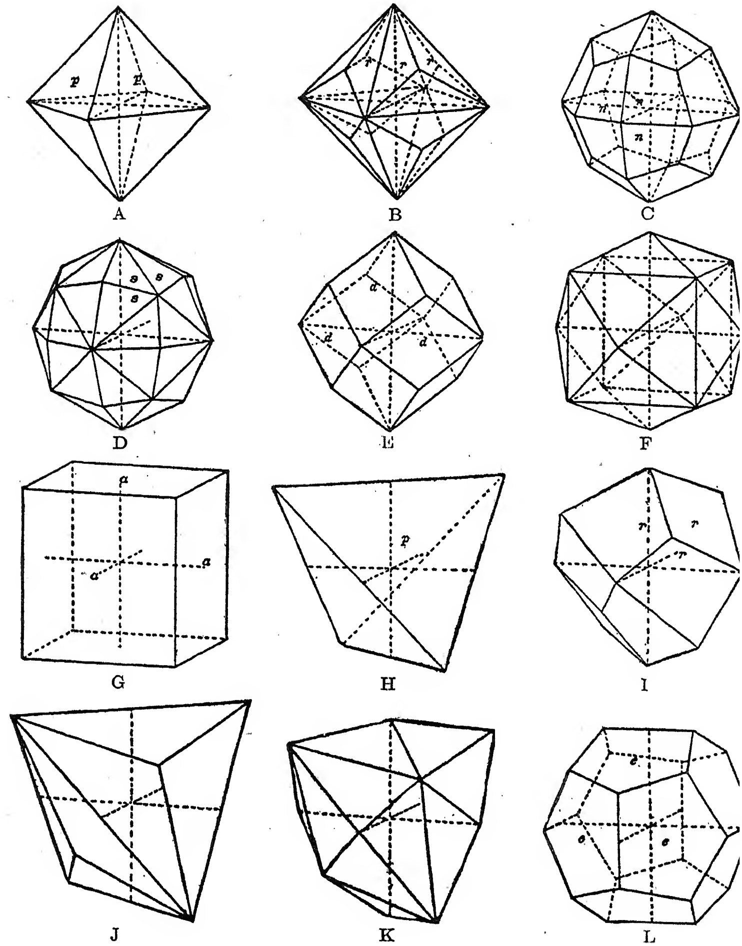


FIG. 20. — *Isometric System.* Principal Forms. The general symbols and tl values of the coefficients for the figures given are added. (After Moses an Parsons.)

Holohedral. (All planes developed.)

A. *Octahedron.* — $a : a : a$.
B. *Trigonal Trisoctahedron.* — $a : a : ma$ ($m = 2$).
C. *Tetragonal Trisoctahedron* or *Trapezohedron.* — $a : ma : ma$. ($m = 2$.)
D. *Hexoctahedron.* — $a : na : ma$.
E. *Dodecahedron.* — $a : a : \infty a$.
F. *Tetrahexahedron.* — $a : na : \infty a$. ($n = 2$.)
G. *Cube* or *Hexahedron.* — $a : \infty a : \infty a$.

Hemihedral.

(In this division only every alternate plai is developed, thus giving only half the nur ber of planes found in the correspondii holohedral form. This is indicated by pr fixing ½ to the symbol.)

H. *Tetrahedron.* — $\frac{1}{2}(a : a : a)$.
I. *Deltohedron.* — $\frac{1}{2}(a : a : ma)$.
J. *Tristetrahedron.* — $\frac{1}{2}(a : ma : ma$
K. *Hextetrahedron.* — $\frac{1}{2}(a : na : ma)$
L. *Pyritohedron.* — $\frac{1}{2}(a : na : \infty a)$.

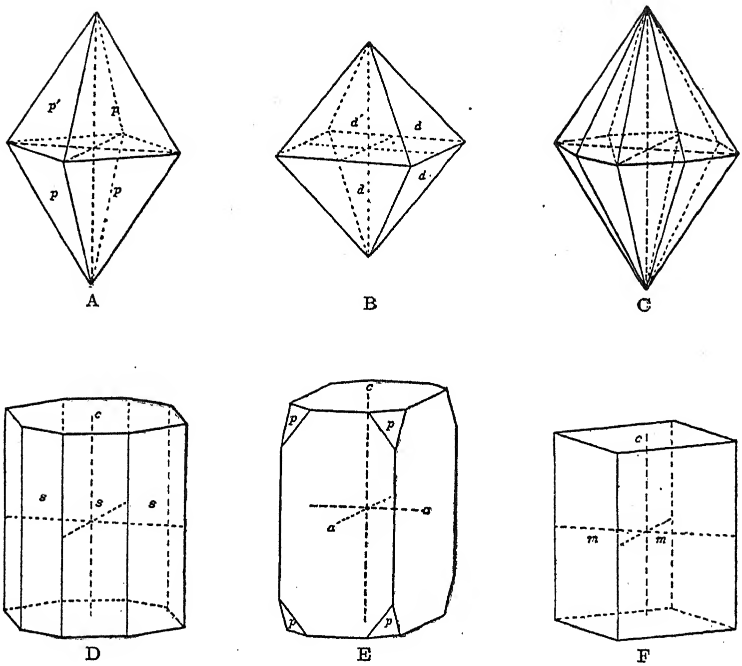
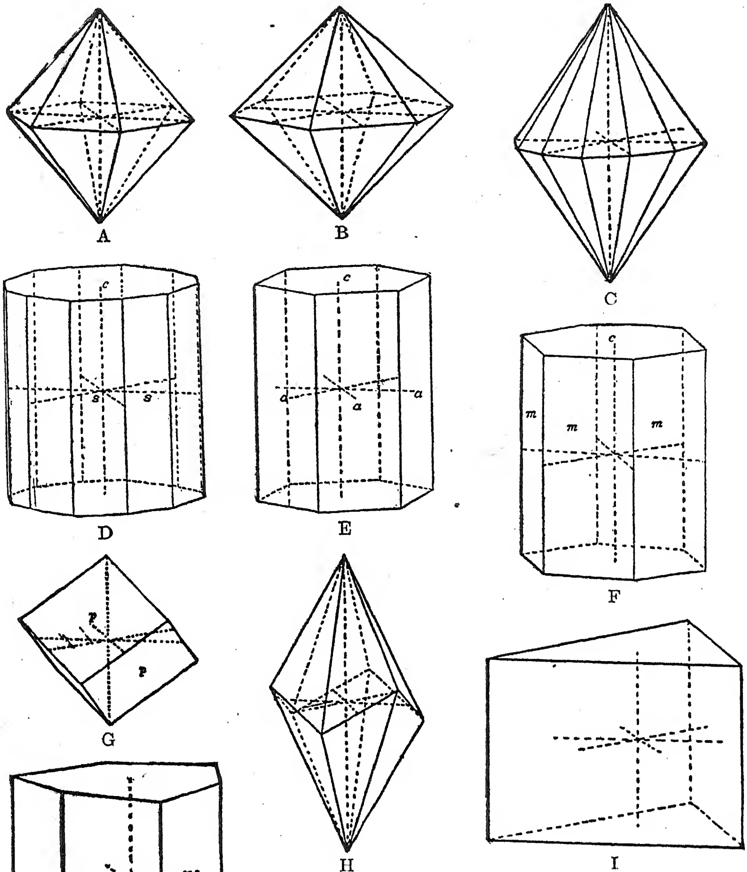


FIG. 21. — *Tetragonal System.* Principal Forms.

(After Moses and Parsons.)

A. *Tetragonal Pyramid, 1st order.* — $a : a : c$.[1]
B. *Tetragonal Pyramid, 2d order.* — $a : \infty a : c$.[1]
C. *Ditetragonal Pyramid.* — $a : na : c$.[1]
D. *Ditetragonal Prism.* — $a : na : \infty c$.
E. *Tetragonal Prism, 2d order.* — $a : \infty a : \infty c$ (with pyramid of 1st order (ρ).— $na : na : mc$).
F. *Tetragonal Prism,* 1st order. — $a : a : \infty c$.
D, E, F, show *Basal Pinacoids* — $\infty a : \infty a : c$.

[1] When occurring in combination a unit length for c is selected and the formula becomes $a : a : mc$.



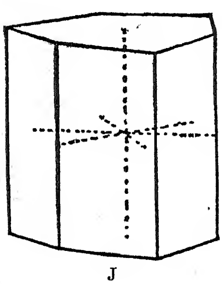


FIG. 22. — *Hexagonal System.* Principal Forms. (After Moses and Parsons.)

Holohedral: (All faces developed.)
A. *Hexagonal Pyramid, 1st order.* — $a : a : \infty a : c.$[1]
B. *Hexagonal Pyramid, 2d order.* — $a : na : na : c.$[1] ($n=2.$)
C. *Dihexagonal Pyramid.* — $a : na : pa : c.$[1]
D. *Dihexagonal Prism.* — $a : na : pa : \infty c.$
E. *Hexagonal Prism, 2d order.* — $a : na : na : \infty c.$ ($n=2.$)
F. *Hexagonal Prism, 1st order.* — $a : a : \infty a : \infty c.$
D, E, F, show *Basal Pinacoids.* — $\infty a : \infty a : \infty a : c.$

Hemihedral. (Half the number of faces developed.)
G. *Rhombohedron, 1st order.* — $\frac{1}{2}(a : a : \infty a : c).$[1]
H. *Scalenohedron.* — $\frac{1}{2}(a : na : pa : c).$[1]
I. *Trigonal Prism, 1st order.* — $\frac{1}{2}(a : a : \infty a : \infty c).$
J. *Ditrigonal Prism.* — $\frac{1}{2}(a : na : pa : \infty c).$
I and J show *Basal Pinacoids.* — $\infty a : \infty a : \infty a : c.$

[1] *mc* in combination; *p* greater than *n*.

IV. Orthorhombic. — Three axes, all of unequal length, but all forming right angles with one another. Fundamental forms: orthorhombic prism $(a : b : \infty c)$; orthorhombic pyramid $(a : b : c)$; etc. (Fig. 23).

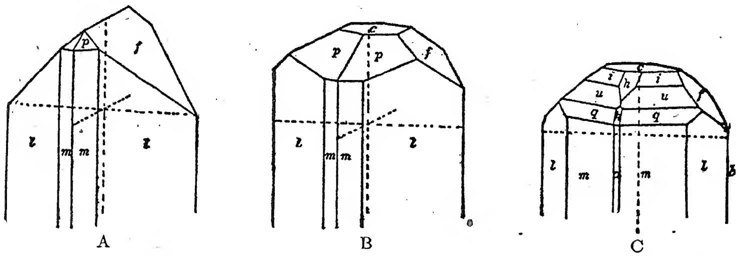


FIG. 23. — *Orthorhombic System.* Principal Forms in combination. (After Moses and Parsons.)

A. *Orthorhombic (unit) Pyramid* (*p*.). — $a : b : c$ (or, $na : b : mc$).
Orthorhombic (unit) Prism (*m*). — $a : b : \infty c$ (or, $na : b : \infty c$).
Brachy-prism (*l*). — $na : b : \infty c$. $(n = 2.)$
Brachy-dome (*f*). — $\infty a : b : c$ (or $\infty a : b : 2 c$).

B. Same forms as in A with addition of *Basal Pinacoid* (*c*): — $\infty a : \infty b : c$.

C. Same forms as in B with addition of two other pyramids (*i*). — $a : b : \frac{2}{3} c$, and (*q*). — $a : b : 2 c$; and two macro-domes (*h*). — $a : \infty b : \frac{2}{3} c$, and (*k*). — $a : \infty b : 2 c$, and a macro-pinacoid (*a*). — $a : \infty b : \infty c$.

V. Monoclinic. — Three axes, all of unequal length, the horizontal ones at right angles to each other, the vertical one (*c*)

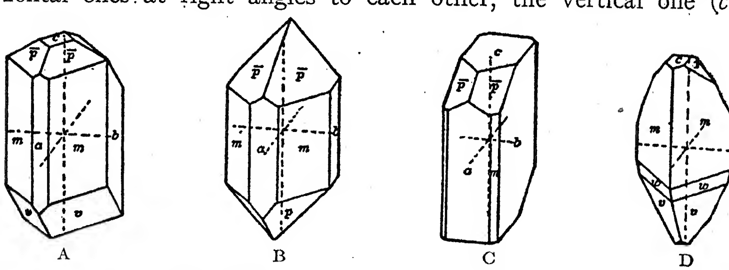


FIG. 24. — *Monoclinic System.* Principal Forms in combination. (After Moses and Parsons.)

A. *Monoclinic (unit) Prism* (*m*). — $a : b : \infty c$ (or, $na : b : \infty c$).
Hemi-pyramid (negative $\bar{p}$, positive *v*). — $a : b : c$ (or, $na : b : mc$).
Ortho Pinacoid (*a*). — $a : \infty b : \infty c$.
Clino Pinacoid (*b*). — $\infty a : b : \infty c$.
Basal Pinacoid (*c*). — $\infty a : \infty b : c$.

B. Same planes as in A, except positive hemi-pyramid (*v*) and basal pinacoids (*c*).

C. Same planes as in A except positive hemi-pyramid (*v*).

D. Unit prism; basal pinacoid; two positive hemi-pyramids *v*. and *w*. $(a : b : 3 c)$ and a clino-dome $z = (\infty a : b : 2 c)$.

inclined with reference to a, but forming a right angle with b. Fundamental forms: monoclinic prism $(a : b : \infty c)$; monoclinic pyramid $(a : b : c)$ (really 2 hemi-pyramids, a positive and a negative one); etc. (Fig. 24).

VI. **Triclinic.** — Three unequal axes all inclined with reference to one another. Fundamental forms: triclinic prism (hemi-prisms) $(a : b : \infty c)$; triclinic pyramid $(a : b : c)$ (Fig. 25).

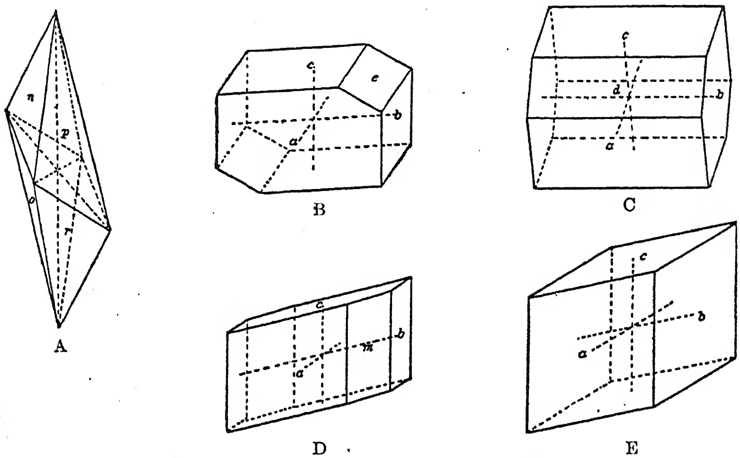


FIG. 25. — *Triclinic System.* Principal Forms. (After Moses and Parsons.)

A. *Triclinic Pyramid.* — $a : b : c$, consists of 4 sets of 2 parallel planes each.

B. *Hemi-brachy-dome* (*e*). — $\infty a : b : c$.[1]
Macro-pinacoid (*a*). — $a : \infty b : \infty c$.
Brachy-pinacoid (*b*). — $\infty a : b : \infty c$.
Basal-pinacoid (*c*). — $\infty a : \infty b : c$.

C. *Hemi-macro-dome* (*d*). — $a : \infty b : c$.[1] Macro- (*a*), Brachy- (*b*), and Basal-pinacoids (*c*).

D. *Triclinic Hemi-prism* (*m*). — $a : b : \infty c$. Macro- (*a*), Brachy- (*b*), and Basal-pinacoid (*c*).

E. Combination of *Macro-* (*a*), *Brachy-* (*b*), and *Basal-pinacoids* (*c*).

Other Physical Characters

Cleavage. — The ability of a mineral to split along one or more planes parallel to actual or possible crystal planes is called *cleavage*, and is an important aid in identifying mineral species.

Fracture. — The mode of breaking in directions other than those of cleavage is the type of fracture of the mineral. It is *conchoidal* (Fig. 41) when it has rounded surfaces suggestive of a shell; *even*

[1] *mc* in combination.

or *uneven*, when nearly plain, or rough and irregular; *hackly* or *splintery*, when it has ragged sharp points and depressions, or separates in a fiber- or splinter-like manner.

Tenacity. — A mineral is *brittle* when it breaks into powder; *sectile*, when small slices can be shaved off which crumble under a hammer; *malleable* when slices from it will flatten under a hammer; *tough*, when great resistance to tearing apart under strain or a blow is shown; *ductile*, when it can be drawn into wire.

Hardness. — The resistance of a smooth plane, whether crystal, cleavage, or fracture, to abrasion is called the hardness, and is commonly determined by scratching the surface. It is expressed in terms of a scale of ten common minerals (Mohs scale). Each mineral will scratch all those softer than itself.

Scale of Hardness

1. Talc	6. Orthoclase
2. Gypsum (Selenite)	7. Quartz
3. Calcite	8. Topaz
4. Fluorite	9. Sapphire
5. Apatite	10. Diamond

Minerals below 2.5 in hardness can usually be scratched with a finger nail; those below 6 by a pocket knife. Any mineral above 5.5 will scratch window glass. By these simple tests hardness can be determined approximately.

Luster. — The brilliancy or shine of a mineral is called its *luster*. It is dependent upon the refractive power, transparency, and structure of the mineral. The following types are recognized:

a. Metallic: luster of metals, gold, silver, copper, etc.

b. Non-metallic luster comprising:

Vitreous — the luster of a fractured surface of glass; example, quartz.

Adamantine — the luster of uncut diamond, zircon, etc., due to high index of refraction.

Resinous — the luster of resin; example, sphalerite.

Greasy — the luster of oiled glass; example, elæolite.

Pearly — the luster of mother of pearl; example, foliated talc.

Silky — the luster of silk; example, satin spar.

Dull — without luster or shine of any kind; examples, chalk, kaolin.

The prefix *sub-* is used to express a lesser degree of the particular luster; *e.g. sub-metallic, sub-vitreous*, etc.

Color. — This depends on chemical composition and is variable; or on physical constitution, when a variety of color-changes with the changes in the direction of light is produced. These are: *Play of color* (opal, labradorite); *Iridescence*, bands of prismatic color; *Tarnish*, surface discoloration; *Opalescence*, milky or pearly reflection; *Asterism*, showing a star by reflected or transmitted light, as in ruby, etc., or in some micas.

Streak. — The color of the fine powder of a mineral is its streak. It is obtained by scratching the mineral or rubbing it upon a smooth, white, and hard surface. (Arkansas stone; streak stone.)

Translucency. — The capacity for transmitting light is the translucency of a mineral. A mineral is *transparent* when objects can be seen through it with clearness; *translucent*, when it transmits light, but objects cannot be seen; *opaque* when no light passes through even the thin edges. *Sub-transparent* and *sub-translucent* are also used.

Specific gravity. — The weight of a substance divided by the weight of an equal volume of distilled water (at 4° C.) is its specific gravity. Exact determinations are made by fine balances, but rough determinations can be made by weighing in the hand and comparing with a mineral of equal size and known specific gravity.

Taste. — Some minerals have a taste, such as *astringent* (alum); *salty* (common salt); *bitter* (epsom salts); *alkaline* (soda); *acid* (sassolite); *cooling* (niter); *pungent* (sal-ammoniac).

Odor. — On heating or burning, some minerals give off odors, of which those of *garlic* (arsenic minerals), *horseradish* (selenium minerals), or *sulphur* are examples. Fetid, bituminous, and argillaceous (clay) odors also occur, the latter noticeable on breathing upon the substance.

Feel. — The response of a mineral to the sense of touch may be *smooth*, *soapy* (talc), *harsh*, *meager* (aluminite), or *cold*, the latter distinguishing gems from glass.

Other Characters. — A few minerals are magnetic, and there is great variation in transmission of heat-rays and of conductivity. Various electric phenomena also exist.

Classification of Minerals

Minerals are classified on a chemical basis, and two distinct methods have been employed which may in general be considered as classifications; first, according to the acid radical (including

oxides, etc.) and second, according to the basic radical. In the first system the minerals are divided into the following classes:[1]

1. Native elements.
2. Sulphides, Selenides, Tellurides, Arsenides, Antimonides.
3. Sulpho salts.
4. Chlorides, Bromides, Iodides, Fluorides.
5. Oxides (Hydroxides, Oxyhydroxides).
6. Carbonates.
7. Silicates.
8. Titano-Silicates, Titanates.
9. Niobates or Columbates, Tantalates.
10. Phosphates, Arsenates, Vanadates, Antimonates.
11. Nitrates.
12. Borates.
13. Uranates.
14. Sulphates, Chromates, Tellurates.
15. Tungstates, Molybdates.
16. Oxalates, Mellitates. (Salts of organic acids.)
17. Hydrocarbon compounds.

Tables of Important Minerals

In the following tabular list, arranged essentially according to the basic radical, the more important minerals are given, with a brief characterization of their essential features. For more details the student is referred to the textbooks cited below.

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7. J. D. DANA. *The System of Mineralogy, Descriptive Mineralogy* by E. S. Dana. John Wiley and Sons, N. Y.
8. W. O. CROSBY. *Tables for the Determination of Common Minerals, Chiefly by their Physical Properties.* Boston. Published by the Author.

[1] Dana, J. D. and E. S.: *The System of Mineralogy.* 6th ed.

Group and Division	Species	Composition	Crystal Form	Cleavage or (Fracture)	Tenacity	Hardness	Luster	Color	Streak	Translucency	Sp. Gr.	Remarks
Iron Minerals												
Sulphides	Pyrrhotite	Fe_nS_{n+1}	hexagonal		brittle	3.5–4.5	metallic	bronze yellow or bronze red	grayish blk.	opaque	4.5–4.6	tarnishes, magnetic
	Pyrite	FeS_2	isometric		brittle	6.–6.5	metallic	brass yellow	greenish blk.	opaque	4.9–5.2	tarnishes
	Marcasite	FeS_2	orthorhombic		brittle	6.–6.5	metallic	pale brass yellow	nearly blk.	opaque	4.6–4.9	darkens on exposure
Oxides	Magnetite	Fe_3O_4	isometric	octahedral ?	brittle	5.5–6.5	metallic to submetallic	black	black	opaque	4.9–5.2	strongly magnetic
	Hematite	Fe_2O_3	hexagonal		brittle, micaceous	5.5–6.5	metallic-dull	blk. to red	brownish red to red	opaque	4.9–5.3	sometimes magnetic
Hydroxides	Goethite	$FeO(OH)$	orthorhombic	(splintery, etc.)	brittle, earthy	5.–5.5	adamant-dull	yel., red, br., blk.	yel., br'sh y.	opaque to transl.	4.–4.4	
	Limonite	$Fe_2(OH)_6.Fe_2O_3$	amorphous		brittle, earthy	5.–5.5	varnish-like, silky-dull	yel., br., blk.	yellowish br.	opaque	3.6–4.	often earthy
Carbonate	Siderite	$FeCO_3$	hexagonal	rhombohedron of 107°	brittle	3.5–4.	vitreous to pearly	gr., yel., br. or blk.	white pale yel.	opaque to transl.	3.83–3.88	often massive, impure
Manganese Minerals												
Oxides	Pyrolusite	MnO_2			rather brittle	1.–2.5	met.-dull	blk. to steel gray	black	opaque	4.7–4.86	
	Psilomelane	$MnO_2+(H_2O.K_2O.BaO)$			brittle	5.–6.	submet. or dull	iron black, dk. gr.	br'sh blk.	opaque	3.7–4.7	botryoidal, stalact. or in layers
Carbonate	Rhodochrosite	$MnCO_3$	hexagonal	par. to rhomb.	brittle	3.5–4.5	vitr.-pearly	pink-red, brown	white	transp. op.	3.3–3.6	efferv. in HCl
Silicate	Rhodonite	$MnSiO_3$	triclinic		brittle	5.5–6.5	vitreous	brownish red to bright red	white	transp. op.	3.4–3.68	
Nickel and Cobalt Minerals												
Sulphides	Pentlandite	$(FeNi)S$	isometric		brittle	3.5–4.	metallic	light bronze yel.	black	opaque	4.6–5.	not magnetic
	Millerite	NiS	hexagonal		elastic cryst.	3.–3.5	metallic	brass or bronze yel.	greenish blk.	opaque	5.3–5.65	hair or needle-like
Sulpharsenide	Cobaltite	$CoAsS$	isometric	cubic	brittle	5.5	metallic	silver wh. to gr.	black	opaque	6.–6.1	
Arsenides	Smaltite	$(CoNi)As_2$	isometric	octahedral	brittle	5.5–6.	metallic	tin wh. to steel gr.	black	opaque	6.4–6.6	usually granular or massive
	Niccolite	$NiAs$.	hexagonal		brittle	5.–5.5	metallic	copper red	br'sh blk.	opaque	7.3–7.67	tarnishes, massive
Silicate	Garnierite	$H_2(Ni.Mg)SiO_4.H_2O$			friable	2.–3.	varnish-like to dull	green to greenish white	lt. gn.-white	opaque	2.27–2.8	unctuous, adheres to tongue

Color abbreviations. — *bl* = blue *blk* = black *br* = brown *col's* = colorless *gn* = green *gr* = gray *orn.* = orange *pk* = pink *pr* = purple *r* = red *vi* = violet *y* = yellow.

Zinc Minerals											
Sulphides	Sphalerite ✓	ZnS	isometric	par. to rhomb. dodecah.	brittle	3.5–4.	resinous	yel., br., black, rarely red, gn., wh.	wh. to pale br.	transp. to transl.	3.9–4.1	
Carbonates	Smithsonite ✓	$ZnCO_3$	hexagonal	par. to rhombohedr. 107°	brittle	5.	vitreous to dull	wh., yel., gn., bl., etc.	white	transl. to opaque	4.3–4.5	stalact., botryoid., porous, granular, etc.
	Hydrozincite	$ZnCO_3.2Zn(OH)_2$			brittle	2.–2.5	dull or pearly	wh., yel.	shining white	opaque	3.58–3.8	incrust, stalact., chalky
Silicates	Willemite	Zn_2SiO_4	hexagonal		brittle	5.	resinous	gn., sulphury, wh., red, gr, br., bl.	nearly white	transp. to opaque	3.89–4.2	often granular
	Calamine	$(ZnOH)_2SiO_3$	orthorhombic		brittle	4.5–5.	vitr. to pearly	y., br., wh., colorless, rarely bl. or gn.	white	opaque to transp.	3.4–3.5	also gran., stalact. botryoid, etc.
Ferrate	Franklinite	$(Zn.Mn)Fe_2O_4$	isometric	parall. to octahedron	brittle	6.–6.5	metal. to dull	black	br. to blk.	opaque	5.–5.2	sometimes slightly magnetic
Tin Mineral											
Oxide	Cassiterite	SnO_2	tetragonal	indist. pyr. and pris.	brittle	6.–7.	adamant. to dull	br. to nearly blk., somet. r., gr. or yellow	wh. pale br.	op. to transl.	6.8–7.1	commonly dull, botryoidal or kidney-shaped masses, pebbles
Titanium Mineral											
Oxide	Rutile	TiO_2	tetragonal		brittle	6.–6.5	ad. to nearly met.	reddish br., r., blk., deep red when transparent	wh., pale br.	op. to transp.	4.15–4.25	hair-like or needle-like cryst. in other minerals
Zirconium Mineral											
Silicate	Zircon	$ZrSiO_4$	tetragonal	imp. par. to pyr., and pris.	brittle	7.5	adamant.	br., reddish, gr. col's, gn. y.	white	transp.-op.	4.68–4.70	small perfect crystals mostly
Cerium and Other Rare Earth Minerals											
Phosphate	Monazite	$(CeLaDi)PO_4$	monoclinic	basal, perfect	brittle	5.–5.5	resinous	clove or red-br., y.	white	op.-transl.	4.9–5.3	small cryst. grains or sand

Group and Division	Species	Composition	Crystal Form	Cleavage or (Fracture)	Tenacity	Hardness	Luster	Color	Streak	Translucency	Sp. Gr.	Remarks
Lead Minerals												
Sulphide	Galenite	PbS	isometric	cubic (easy)	brittle	2.5	metallic	lead-gray	lead-gray	opaque	7.4–7.6	heavy, generally large cleavable masses
Sulphate	Anglesite	$PbSO_4$	orthorhombic	basal, prism	very brittle	3.	ad.-vitr.	col's, wh., gr., rarely y., bl., gn.	white	transp.-opaque	6.12–6.39	also compact, granular, etc.
Carbonate	Cerussite	$PbCO_3$	orthorhombic	par. to prism, brachy-dome	very brittle	3.–3.5	ad.-silky	wh., gr., col's, col. by imp.	white	transp. or transl.	6.46–6.51	also fibrous granular, compact, earthy
Bismuth Minerals												
Metal	Bismuth	Bi	hexagonal		sectile to brittle	2.–2.5	metallic	red'sh, silver wh.	silver, white	opaque	9.7–9.83	often branching shapes or isolated grains
Oxide	Bismite	Bi_2O_3	orthorhombic				dull	gray, gn'sh or y'sh wh.	white	opaque		powder or earthy
Arsenic Minerals												
Sulphides	Orpiment	As_2S_3	orthorhombic	plates or leaves	sl. sectile	1.5–2.	res.-pearly	lemon yellow	lemon yellow	transl. to nearly opaque	3.4–3.6	foliated, cl. into flexible scales, also granular reniform or crystals
	Realgar	As_2S_2	monoclinic		sl. sectile	1.5–2.	resinous	aurora red to orange red on exposure	orange red	transl. to transp.	3.4–3.6	also granular and compact
Sulph-arsenide	Arsenopyrite	$FeAsS$	orthorhombic		brittle	5.5–6.	metallic	silver wh. to steel gr.	grayish blk.	opaque	6.–6.2	usually comp. or granular or in grains
Antimony Mineral												
Sulphide	Stibnite	Sb_2S_3	orthorhombic	brachy-pin.	brit.-sect.	2.	metallic	lead gr. often iridescent tarnish	lead gray	opaque	4.52–4.62	imp. cryst. columnar or bladed, needle-like or granular

Vanadium Mineral											
Vanadate	Vanadinite	$Pb_5Cl(VO_4)_3$	hexagonal		brittle	3.	res. on fracture	deep red, bright red, y., br.	wh. to pale yel.	op. to transl.	6.66–7.23	small sharp crystals and masses of crys.
Uranium (and Radium) Minerals											
Uranate	Uraninite (Pitch blende)	$2UO_3.UO_2(?)$	isometric		brittle	5.5	pitch-like to sub-met.	some shade of black	gr., olive-gn., dk.br.	opaque	6.5–9.7	massive botryoidal or granular
Vanadate	Carnotite	$(K_2Ca)2UO_3.V_2O_5.3H_2O(?)$						canary lemon or lemon yellow				minute scales or in interstices of sandstones; easily sol. in acid
Chromium Mineral											
Chromate	Chromite	$FeCr_2O_4$	isometric		brittle	5.5	sub-met. to met.	black	dark brown	opaque	4.3–4.6	usually massive or dissem. grains, sometimes slightly magnetic
Molybdenum Minerals											
Sulphide	Molybdenite	MoS_2	hexagonal	basal	sect. mall.	1.–1.5	metallic	bluish lead gray	greenish	opaque	4.6–4.9	thin graphitic scales
Oxide	Wulfenite	$PbMoO_4$	tetragonal			3.	resinous	y. orn. or bright orange red	white	sub-tr'p. to sub-tr'l.	6.7–7.	thin square crystals
Tungsten Minerals											
Tungstenates	Wolframite	$(FeMn)WO_4$	monoclinic	perfect in one dir.		5.–5.5	res. to sub-met.	dark gray, blk., red-brown	dark br., y'sh br., gr.	op. to transl.	6.8–7.55	heavy dark crystals of orthorhombic appearance
	Scheelite	$CaWO_4$	tetragonal	dist. 1st ord. pyr., indist. 2d ord. pyr.	brittle	4.5–5.	adamant.	pale y., gr., br., wh. or green	white	transp.-opaque	5.4–6.1	also drusy crusts
Copper Mineral											
Metal	Copper	Cu.	isometric		malleable ductile	2.5–3	metallic	copper red, tarnish nearly blk.	copper red	opaque	8.8–8.9	in sheets or disseminated masses, threads, wires and crystals

Group and Division	Species	Composition	Crystal Form	Cleavage or (Fracture)	Tenacity	Hardness	Luster	Color	Streak	Translucency	Sp. Gr.	Remarks
Copper Minerals—*Con.*												
Sulphides	Chalcocite	Cu_2S	orthorhombic		brittle	2.5–3.	metallic	blackish lead gray, dull-blk. tarnish	lead gray	opaque	5.5–5.8	granular or compact, nodules, pseudomorphs
	Bornite	Cu_5FeS_4	isometric		brittle	3.	metallic	dark copper red, brownish or violet blue often varied	grayish blk.	opaque	4.9–5.4	usually massive, peacock tarnish
	Chalcopyrite	$CuFeS_2$	tetragonal		brittle	3.5–4.	metallic	bright brass yel. tarnish blue, purple-blk. hues	greenish blk.	opaque	4.1–4.3	usually massive
Sulphoantimonite	Tetrahedrite	$Cu_8Sb_2S_7$	isometric		brittle	3.–4.5	metallic	light steel to dark lead gr. or iron blk.	blk. or red br.	opaque	4.5–5.1	
Oxide	Cuprite	Cu_2O	isometric		brittle	3.5–4.	adamant. or dull	crimson scarlet, vermilion or brownish red	brownish red	transp. to opaque	5.85–6.15	also capillary
Carbonates	Malachite	$Cu_2(OH)_2CO_3$	monoclinic		brittle	3.5–4.	silky, adam. dull	bright emerald, grass gn. or nearly blk.	pale green	transl. to opaque	3.9–4.03	often silky, fibrous banded, stalact. earthy
	Azurite	$Cu_3(OH)_2(CO_3)_2$	monoclinic		brittle	3.5–4.	vitreous	dark blue to azure blue	blue	transl.-opaque	3.77–3.83	also massive, velvety or dull earthy
Silicate	Chrysocolla	$CuSiO_3.2H_2O$			brittle	2.–4.	vitr. dull	gr., light blue, br. when ferruginous	white to pale blue	transl.-opaque	2.–2.3	incrustations, kaolin-like, never crystals
Mercury Mineral												
Sulphide	Cinnabar	HgS.	hexagonal		brit.-sect.	2.–2.5	adam.-dull	cochineal r., scarlet, red-br., blackish	scarlet	opaque-transp.	8.–8.2	generally granular masses
Silver Minerals												
Metal	Silver	Ag.	isometric		malleable	2.5–3.	metallic	silver wh., tarnish br. to nearly black	silver white	opaque	10.1–11.1	masses, scales, wire-like, needles, arborescent groups

Sulphide	Argentite	Ag_2S	isometric		very sect.	2.–2.5	metallic	lead gray to blk. or blackish gr.	lead gray	opaque	7.2–7.36	cuts like wax, massive, disseminated grains, incrusting or crystals
Sulpho-arsenite	Proustite	Ag_3AsS_3	hexagonal		brittle	2.–2.5	adamant. brilliant	scarlet vermilion	scarlet	transl. transp.	5.57	usually disseminated through gangue or as crust
Sulphoanti-monite	Stephanite	Ag_5SbS_4	orthorhombic		brittle	2.–2.5	metallic	black	black	opaque	6.2–6.3	fine grained, often dissem. thr. gangue
Chloride	Cerargyrite	AgCl	isometric		very sect.	1.–1.5	waxy, res.	pearl gray or greenish, darkens on exposure to light to vi., br., blk.	shining white	transl.	5.–5.5	crust or coating, horn or wax-like
Gold Minerals												
Metal	Gold	Au	isometric		malleable	2.5–3.	metallic	golden yellow to nearly silver white	like color	opaque	15.6–19.3	nuggets, grains, scales, wire-like net-like dendritic rarely crystals
Telluride	Sylvanite	$(Au.Ag)Te_2$	monoclinic		brittle	1.5–2.	dull	steel gray to silver	like color	opaque	7.9–8.3	massive granular
Platinum, etc.												
Metal	Platinum	Pt.	isometric		malleable	4.–4.5	metallic	light steel gray	steel gray	opaque	14.–19.	small grains and nuggets in alluvial sands
	Iridosmine	Ir.Os.	hexagonal		rather brit.	6.–7.	metallic	tin white to gray	like color	opaque	19.3–21.1	irregular flattened grains and hexagonal plates
Aluminum Minerals												
Fluoride	Cryolite	$AlNa_3F_6$	triclinic	basal and prismatic nearly 90°	brittle	2.5	vitr. wax-like	colorless, white, br.	white	transl. transp.	2.95–3.	resembling spermaceti or white wax
Oxide	Corundum	Al_2O_3	hexagonal	rhombohedral 86°4′	brittle to tough	9.	vitr. or adam.	bl., red, gn., yel., blk., br., white	white	transp.-opaque	3.95–4.11	incl. sapphire, ruby, adamantine spar, emery
Hydroxide	Gibbsite	$Al(OH)_3$	monoclinic		brittle to tough	2.5–3.5	faint vitr.	white greenish, reddish, yel.	white	transl.	2.38	usually in stalactites or thin crusts, fibrous internal structure

Group and Division	Species	Composition	Crystal Form	Cleavage or (Fracture)	Tenacity	Hardness	Luster	Color	Streak	Translucency	Sp. Gr.	Remarks
Aluminum Minerals — *Con.*												
Oxyhydroxide	Bauxite	$Al_2O(OH)_4$			brittle	1.–3.	dull, earthy	white, red, yel., br., blk.	like color	opaque	2.4–2.5	usually pisolitic porous or compact earthy and clay-like
Phosphate	Turquois	$Al_2(OH)_3PO_4.H_2O$			brittle	less than 6	dull and waxy	sky bl. to greenish bl. shades of gn.	white to bluish wh.	opaque	2.42–2.89	nodules, veins, druses
Sulphate	Alunite	$(AlOH)_3.K.(SO_4)_2.+3H_2O$	rhombohedral		brittle	3.5–4.	vitreous	wh., grayish reddish	white	transp.–nearly op.	2.58–2.75	fibrous and tabular masses or crystals
Potassium Minerals												
Chlorides	Sylvite	KCl	isometric	cubic	brittle	2.	vitr.	col's, wh., bluish reddish	white	transp, when pure	1.97–1.99	tastes like salt
	Carnallite	$KCl.MgCl_2.6H_2O$	orthorhombic		brittle	1.	sub-vitreous	wh., brownish, reddish	white	transl.–transp.	1.62	tastes salty and bitter
	Kainite	$KCl.MgSO_4.3H_2O$	monoclinic		brittle	2.5–3.	vitreous	wh. to red-wh. col's	colorless	transp.–transl.	2.05–2.2	tastes salty and astringent
Sodium Minerals												
Chloride	Halite	$NaCl$	isometric	cubic	brittle	2.5	vitreous	wh. col's, yel., br., bl.	white	transl.–transp.	2.4–2.6	tastes salty: massive granular impure
Sulphate	Mirabilite	$Na_2SO_4.10H_2O$	monoclinic		brittle	1.5–2.	vitreous	wh. or faint greenish	white	transp.–op.	1.48	taste salty and bitter, fibrous crusts
Nitrate	Soda Niter	$NaNO_3$	hexagonal		brittle	1.5–2.	vitreous	col's, wh. yellowish	white	transp.	2.24–2.29	taste cooling, salty; granular crusts or masses
Lithium Minerals												
Silicates	Spodumene	$LiAl(SiO_3)_2$	monoclinic		brittle	6.5–7.	vitreous	wh., pale-gn., emerald green, pink, purple	white	transp.–op.	3.13–3.20	sometimes enormous crystals
	Lepidolite	$R_3Al(SiO_3)_3$	monoclinic	basal	sectile	2.5–4.	pearly	rose, violet, lilac, gr., wh.	white	transl.	2.8–2.9	scaly, granular, pink mica

Barium Minerals												
Sulphate	Barite	$BaSO_4$	orthorhombic	basal, prismatic	brittle	2.5–3.5	vitr. pearly	wh., light shades yellow, br., r., bl.	white	transp.–op.	4.3–4.6	also granular, fibrous, earthy, stalactic, nodular
Carbonate	Witherite	$BaCO_3$	orthorhombic		brittle	3.–4.	vitreous	wh., gr., yellowish	white	transl.	4.29–4.35	also massive granular, nodular, columnar
Strontium Minerals												
Sulphate	Celestite	$SrSO_4$	orthorhombic	basal and prismatic	brittle	3.–3.5	vitr.–pearly	wh., col's, pale-bl., reddish	white	transp.–nearly op.	3.95–3.97	crystals and fibrous cleavable masses, rarely granular
Carbonate	Strontianite	$SrCO_3$	orthorhombic		brittle	3.–3.5	vitr.	pale yellowish, greenish-white, also gn. gr. col's	white	transl.	3.68–3.72	usually radiating needle-like crystals
Calcium Minerals												
Fluoride	Fluorite	CaF_2	isometric	octahedral	brittle	4.	vitreous	wine-y., gn., vi., bl. col's, br., blk.	white	transp.–nearly op.	3.01–3.25	usually in cubes
Sulphates	Anhydrite	$CaSO_4$	orthorhombic	at right angles	brittle	3.–3.5	vit., pearly	wh., gr., bluish, brick-red	white	transl.–op.	2.9–2.98	granular, fibrous, lamellar massive
	Gypsum	$CaSO_4.2H_2O$	monoclinic	perfect: clinopin. others less so	brittle laminæ flex.	1.5–2.	pearly, silky, vitr.	wh., col's, gr., r., y., br.	white	transp.–op.	2.31–2.33	cryst. massive, fibrous, scaly, etc.
Carbonates	Aragonite	$CaCO_3$	orthorhombic	br.-pin. prism, br.-dome	brittle	3.5–4.	vitreous	wh., vi., y., pale gn.	white	transl.–transp.	2.93–2.95	cryst. columnar, needle, oölitic, stalactic, coral-like, etc.
	Calcite	$CaCO_3$	hexagonal	rhombohedral	brittle	3.	vitr.–dull	y., wh., col's pale red, gn., bl.	white	transp.–op.	2.71–2.72	massive, crystals, stalact., etc.
	Dolomite	$CaCO_3.MgCO_3$	hexagonal	rhombohedral	brittle	3.5–4.	vitr. pearly	wh., pk., gn'sh gr., br., blk.	white	transl.–op.	2.8–2.9	cryst., massive, granular, etc.
Magnesium Minerals												
Oxide	Spinel	$Mg(AlO_2)_2$	isometric	octahedral, difficult	brittle	8.–8.5	vitr.	ruby, rose r., pink, y. to gr., bl., pr.-vi.	white	transp.–transl. (opaque)	3.5–3.7	gem stone when of good quality

Group and Division	Species	Composition	Crystal Form	Cleavage or (Fracture)	Tenacity	Hardness	Luster	Color	Streak	Translucency	Sp. Gr.	Remarks
Magnesium Minerals —*Con.*												
Sulphates	Epsomite	$MgSO_4.7H_2O$	orthorhombic		brittle	2.–2.5	vitr. dull	white	white	transp.–transl.	1.75	delicate white, fibrous, efflorescence, earthy white crust, bitter taste
	Kieserite	$MgSO_4.H_2O$	monoclinic		brittle	3.–3.5	vitr. dull	wh. yellowish	white	transl.	2.52–2.57	coarse to fine granular or compact
Carbonate	Magnesite	$MgCO_3$	hexagonal	(conchoidal)	brittle	3.5–4.5	dull vit. silky	wh. yel. br.	white	opaque–transl.	3.–3.12	porcelain-like masses, nodules, marble-like
Boron Minerals												
Acid	Sassolite	H_3BO_3	monoclinic		brittle	1.	pearly	wh. yellowish	white	transl.	1.43	also small wh. or yellowish scales, stalact, acid taste, unctuous feel
Borates	Ulexite	$Ca.Na.B_5O_8.8H_2O$			brittle	1.	silky	white	white	transl.	1.65	rounded masses (cotton balls) of silky fibres
	Colemanite	$Ca_2B_6O_{11}.5H_2O$	monoclinic	clino-pinacoidal	brittle	4.–4.5	vitr.–dull	wh. or col's	white	transp.–opaque	2.26–2.48	cryst. and compact masses, porcelain or chalk-like
Sulphur Mineral												
Element	Sulphur	S	orthorhombic	basal, prism and pyr. imperfect	brittle	1.5–2.5	resinous	y. yellowish-orn., br., gr.	white, pale yel.	transp.–transl.	2.05–2.09	also crusts, stalactites, spheres, powder
Hydrogen Mineral												
Oxide	(Water) Ice	H_2O	hexagonal		brittle	1.5	vitreous	wh., col's, pale blue	colorless	transp.	0.91	melts at 0° C., boils at 100° C. (press. 760 mm.)

Phosphorus Mineral Phosphate	Apatite	$Ca_5(ClF)(PO_4)_3$	hexagonal	imperf. basal; prismatic	brittle	4.5–5	vitr. to res.	gn., r., br., y., vi., wh., col's	white	transp.–opaque	3.17–3.23	cryst. compact, nodular, etc.
Carbon and Hydro-Carbons Element	Graphite	C	hexagonal	basal into plates	scales flex. slightly sect.	1.–2.	met.-dull	black–dark gray	dark gray	opaque	2.09–2.25	unctuous, marks paper, mostly in flakes or compact masses
	Diamond	C	isometric	octahedral	brittle	10.	adamant	col's, bluish tinged y., br., gn. and blk.	col's	transp.–opaque	3.145–3.518	high index of refraction
Hydro-carbons	Ozokerite	C_nH_{2n+2}		(conchoidal)	waxy	abt. 2	waxy	br. to nearly blk., sometimes opalescent		opaque	0.93–0.95	like wax, foliated
	Amber, etc.			(conchoidal)	brittle	2.5	resinous	y., reddish, brownish, whitish		transp.–transl.	1.065–1.081	in amorphous masses
	Mineral coal impure			(conchoidal)	brittle	0.5–2.5	sub-met. to earthy	blk.–brownish blk.	black	opaque–sub-transl.	1.–1.8	in beds and amorphous masses
Silica and Rock-forming Silicates Silica	Quartz	SiO_2	hexagonal	difficult rhomb.	brittle	7.	vitreous	col's and all colors	white	transp.–opaque	2.65–2.66	cryst. and fragments in rock, sand, etc.
	Chalcedony	SiO_2		(conchoidal)	brittle	6.5–7.	waxy	all colors	white	transl.–opaque	2.62–2.64	amorphous botryoidal, etc.
	Opal	$SiO_2.nH_2O$			brittle	5.5–6.5	vit. prl.–dl.	col's and all colors	white	tr'sp.-op.	2.1–2.2	opalescent
Feldspars	Orthoclase	$KAlSi_3O_8$	monoclinic	right-angled	brittle	6.–6.5	vit.–pearly	flesh-red, yellowish, wh., col's, gr., gn.	white	transp.–opaque	2.44–2.62	generally cleavable masses also compact
	Plagioclase	$m(NaAlSi_3O_8) + n(CaAl_2Si_2O_8)$	triclinic	at 86° approx.	brittle	5.–7.	vitr.–pearly	various	white	transl.–opaque	2.5–2.8	see table in next chapter
Feldspathoids	Leucite	$KAl(SiO_3)_2$	isometric		brittle	5.5–6.	vitr.–greasy	wh., gray, yel. and red tints	white	transl.–opaque	2.45–2.50	disseminated grains and crystals
	Nephelite	$7NaAlSiO_4.NaAl(SiO_3)_2$	hexagonal	prismatic, basal	brittle	5.5–6.	vitr.–greasy	wh., col's, reddish, brownish, greenish-gray	white	transl.–opaque	2.55–2.65	grains or crystals

Group and Division	Species	Composition	Crystal Form	Cleavage or (Fracture)	Tenacity	Hardness	Luster	Color	Streak	Translucency	Sp. Gr.	Remarks
Rock-forming Silicates —*Con.*												
Pyroxenes	Pyroxene	$RSiO_3$	monoclinic	prismatic 87°10′	brittle	5.–6.	vitr. dull, resinous	wh., gn., blk., br.	wh.–greenish	op.–transp.	3.2–3.6	crystals, foliated, etc.
	Wollastonite	$CaSiO_3$	monoclinic	good	brittle	4.5–5.	vitr., etc.	wh., gray	white	transl.	2.8–2.9	cleavable to fibrous
Amphibole	Amphibole	$RSiO_3$	monoclinic	prismatic, 124°11′	brittle	5.–6.	vitr.–silky	wh., gr., gn., blk., br., yel., red	wh. or greenish	transp.–op.	2.9–3.4	cryst. to fibrous (asbestos)
Garnet, etc.	Garnet	$R''_3R'''_2(SiO_4)_3$	isometric	dodecah. imperfect	brittle	6.5–7.5	vitr.–res.	br., blk., vi., y., r., wh., gn.	white	transp.–op.	3.15–4.38	crystals or granular, also grains
	Vesuvianite	$Ca_6[Al(OH,F)]Al_2(SiO_4)_6$	tetragonal	indist. prism. and basal	brittle	6.5	vitr.–res.	br., gr., rarely y., bl.; dichroic	white	transl.–op.	3.35–3.45	also columnar, granular, compact
Olivine group	Chrysolite	$(MgFe)_2SiO_4$	orthorhombic		brittle	6.5–7.	vitreous	yellowish-gn., brownish red	white–yellowish	transp.–transl.	3.27–3.57	generally as granular masses or disseminated grains
Scapolite gr.	Wernerite	Ca.Al. Silicate	tetragonal	paral. both prisms	brittle	5.–6.	vitr.–dull	gr., gn., wh., bluish, reddish	white	op.–transl.	2.66–2.73	large cryst., columnar, granular
Andalusite gr., etc.	Andalusite	$Al(AlO)SiO_4$	orthorhombic	prism imper., 90°48′	brittle	7.–7.5	vitreous	rose-red, flesh-r., vi., pale gn., wh., pearl gray	white	transp.–op.	3.16–3.20	crystals, with cross on section (Chiastolite)
	Sillimanite	$Al(AlO)SiO_4$	orthorhombic	brachy-pinacoidal	tough	6.–7.	vitreous	br., gr., greenish	white	transp.–transl.	3.23–3.24	long almost fibrous crystals, fibrous columnar masses
	Cyanite	$(AlO)_2SiO_3$	triclinic	par. to 3 pinacoids	brittle	5.–7.	vitreous	bl., wh., gr., gn., nearly blk.	white	transl.–transp.	3.56–3.67	long blade-like crystals
	Staurolite	$Fe(AlO)_4(AlOH)(SiO_4)_2$	orthorhombic		brittle	7.–7.5	res.–vitr.	dark. br., blk.-br., gray when weathered	white	transl.–op.	3.65–3.75	often forms cross by twinning
Beryl etc.	Beryl	$Be_3Al_2(SiO_3)_6$	hexagonal	imper. basal and prism	brittle	7.5–8.	vitreous	emerald to pale gn., bl., y., wh., r., col's	white	transp.–nearly op.	2.63–2.8	var.: emerald, bright green; aquamarine, sky-blue-greenish bl.
	Topaz	$Al(Al(O.F_2))SiO_4$	orthorhombic	basal perfect	brittle	8.	vitreous	col's, y., pale-bl., gn., wh., pk.	white	transp.–nearly op.	3.4–3.65	crystals, massive, worn fragments in sand
	Tourmaline	$R_{18}B_2(SiO_5)_4$	hexagonal	difficult	brittle	7.–7.5	vitr. res.	blk., br., gn., bl., r., col's	white	transp.–op.	2.98–3.20	sections of crystal often triangular

R (in Pyroxenes etc.): Ca, Mg, Mn, Fe, Al, Na, K; (in Tourmaline): Al, K, Mn, Ca, Mg, Li; R'' = Ca, Mg, Fe, Mn; R''' = Al, Fe''', Cr, (Ti).

	Titanite	$CaSiTiO_5$	monoclinic	prismatic easily, pyr. less easy	brittle	5.–5.5	adam. to res.	br., blk, y., gn., rarely rose r.	white	transp.–op.	3.4–3.56	tabular crystals
	Epidote	$Ca_2Al_2(Al.OH)(SiO_4)_3$	monoclinic	basal, easy	brittle	6.–7.	vitreous	yel., gn., nearly blk., wh., r., gr.	white	transp.–op.	3.25–3.5	also coarse and fine granular masses, fibrous
Zeolite gr.	Natrolite	$Na_2Al(AlO)(SiO_3)_3.2H_2O$	orthorhombic	prismatic	brittle	5.–5.5	vitreous	col's, wh., y., r.	white	transp.–op.	2.2–2.25	slender prisms in radiating clusters
	Stilbite	$H_4(Na_2Ca)Al_2(SiO_3)_6.4H_2O$	monoclinic	par. to pearly face	brittle	3.5–4.	vitr. pearly	y., br., wh., r.	white	transl.	2.09–2.2	tabular crystals, sometimes globular or radiated in sheaf-like groups
	Apophyllite	$H_{14}K_2Ca_8(SiO_3)_{16}.9H_2O$	tetragonal	basal	brittle	4.5–5.	vitr.–pearly	col's, pk., wh., greenish	white	transp.–nearly op.	2.3–2.4	flat cryst., and plates, lamellar masses
	Prehnite	$H_2Ca_2Al_2(SiO_4)_3$	orthorhombic	basal	brittle	6.–6.5	vitreous	light to dark gn., grayish wh.	white	transl.	2.8–2.95	sheaf-like groups of tabular crystals
	Datolite	$Ca(B.OH)SiO_4$	monoclinic		brittle	5.–5.5	vitreous	col's, white, greenish	white	transl.–nearly op.	2.9–3.	glassy crystals
Mica gr.	Muscovite	$H_2(K.Na)Al_3(SiO_4)_3$	monoclinic	basal, eminent	elastic	2.–2.5	vitr.–pearly on cleav.	gr., br., gn., y., vi., r., blk.	white	transp. in laminæ	2.76–3.	splits into excessively thin elastic laminæ
	Biotite	$(H.K)_2(MgFe)_2Al_2(SiO_4)_3$	monoclinic	basal, eminent	tough–elastic	2.5–3.	pearl.–vitr. sub.-met.	commonly blk. to green	white	transp.–op.	2.7–3.1	differs from preceding in color
	Phlogopite	$R_3Mg_3Al(SiO_4)_3$ (R=H, K, Mg, F)	monoclinic	basal-eminent	tough elastic	2.5–3.	pearly–sub. met.	yel.-brown, brown r., gn., col's	white	transp.–transl.	2.78–2.85	amber or bronze color thin plates show star on transmitted light
Chlorite gr.	Prochlorite	$H_{40}(Fe.Mg)_{23}Al_{14}Si_{13}O_{90}$	monoclinic	easy into plates	brittle	1.–2.	feebly pearly	dark gn., grass-green, olive gn.	whitish or greenish	transl.–op.	2.78–2.96	mass of fine scales also crystals
Hydr.Sil.Mg.	Serpentine	$H_4Mg_3Si_2O_9$			brittle	2.5–4.	greasy–waxy, silky	gn., y., br., r., blk., variegated	white	transl.–op.	2.5–2.65	no crystals, massive fibrous etc.
	Talc	$H_2Mg_3(SiO_3)_4$	monoclinic	into non-elastic plates	sectile	1.–4.	pearl–wax-like	wh., greenish, gr., br., r.	white	transl.	2.55–2.87	soft, soapy, foliated to fibrous
Hydr. Sil. Al.	Kaolinite	$H_4Al_2Si_2O_9$	monoclinic		brittle	2.–2.5	dull or pearly	wh., y., br., r., bl.	white or yellowish	op.–transl.	2.6–2.63	compact clay-like rarely cryst.

CHAPTER V

ROCKS, THEIR CLASSIFICATION AND PRINCIPAL TYPES

Definitions

A rock may be defined as a mineral mass or an association of minerals, which in their natural occurrence form an essential part of the earth's crust. This distinction is not a very precise one, especially when the material of the rock consists of only one mineral. Thus the calcite in a vein would be considered a mineral, while essentially the same material in a bed of marble would be considered a rock. We shall see, however, as we proceed with the discussion of the rocks, that in practice the distinction between rock and mineral can as a rule be readily made.

Age Relations of Rocks

It will be useful at this early stage of our study to recognize the fact that the rocks of the earth's crust are of various ages. Some, like the rocks which make up the Adirondack Mountains, Pikes Peak in Colorado, the Highlands of the Hudson, the Scottish Highlands, the main mass of Finland, and a great part of central France, etc., are very old; others, like those of the "puys" which are scattered over the central French region, the basalts of the Columbia and Snake River plateaus of the northwestern United States, the rocks immediately underlying Paris, London, Vienna, and Berlin, and the rocks of southern Florida are very young, though not all of the same age. It is possible to divide the history of the earth into a number of periods and eras, just as human history can be divided. But whereas the successive periods of human history are measured by centuries at the most, those of the pre-human earth history are measured by hundreds of thousands if not by millions of years. And as we can refer the monuments and buildings of human origin to their successive periods in human history, often from the character of these monuments and buildings themselves,

so we can refer most of the different rocks and rock structures of the earth's crust to their respective geological periods, or to the period of the earth's history when they came into existence as rocks. It is desirable that the student should begin to familiarize himself at this point with the names of the different periods of earth history

Fig. 26. — Ledge of glaciated rock overlain by glacial drift, showing the sharp contact line between the bed-rock and the mantle-rock. New York City. (F. K. Morris, Photo.)

as given in the table in Chapter XXIV of this book. At a later stage of his studies he will learn by what means it becomes possible to refer rocks and rock structures to their proper period. When in the succeeding pages we refer to the geological age of any rock mass the student should consult the table until he has become familiar with the succession of the periods. (See p. xviii.)

Bed-Rock and Mantle-Rock

In general we may distinguish between the *solid* or *bed-rock* and the *unconsolidated rock* or rock material, which latter is commonly called the *mantle-rock* because it covers or mantles the bed-rock which everywhere underlies it and projects through it as ledges. The mantle-rock is of course much younger than the bed-rock upon which it rests. In the northern United States and Canada and the northwestern part of Europe, the mantle rock generally rests abruptly upon the solid or bed-rock, the contact line between the two being commonly sharp (Fig. 26). In many other por-

tions of the earth, however, there is a gradation between the two, the mantle-rock becoming more stony downwards, and passing into rotten rock and finally into fresh bed-rock. This relationship will be discussed more fully in a subsequent chapter; the present one will only take account of the solid rock which forms all except the surface film of the crust of the earth.

Classifications of Rocks

General Principles of Classification. — Classification of natural objects may be made either on a natural or on an artificial basis. A natural classification is based on the origin and development of the objects classified or on their *genesis*. Such a classification is therefore called a *genetic* one, and it alone has a permanent scientific value. It is true that a genetic classification can be made only when the genesis or origin of the objects classified has been determined, and that therefore the artificial systems of classification will always precede the scientific or genetic one. The artificial classification is generally based upon the possession in common, by the objects classified, of a single character or, at most, a few characters. Thus whales were formerly classified with fish because, like these, they lived in the water and had a fish-like form. Their true relationship is, however, more closely with elephants, both being mammals. The *eel-grass* of our coast is not a grass, but belongs to the family of water lilies, although its leaves are grass-like. Rock-salt and sandstone have little in common, though generally classified together as sedimentary rocks; both may have been deposited in lagoons near the seashore, and therefore in a sense are sediments.

In general, it may be said that the progress of any science is indicated by the replacement of the original artificial by the natural or genetic classification. Thus as the study of plants developed into the science of botany, the original artificial classification of plants, based on the number of stamens of the flower, and on other superficial characters, became superseded by the natural classification, which is based upon community of origin of the members of the same group; and in zoölogy, we find that artificial classifications, based on superficial resemblances or the possession of a common character, are constantly discarded as the true *genetic* or natural relationships of animals are becoming more fully understood.

A Convenient Artificial Classification of Rocks

A convenient classification of rocks, which has come into general use, recognizes three fundamental divisions, as follows:

1. *Igneous Rocks.* Rocks which result from the cooling of a molten mass, or *magma*, either upon the surface of the earth, or within the crust at greater or less depths. An example of the first is *basaltic lava*; of the second, *granite*.

2. *Sedimentary Rocks.* Rocks which were formed (*a*) as mechanical sediments in water or air, (*b*) as chemical precipitates and evaporation products from solution in water, and (*c*) as deposits formed by organisms either in water or air. Examples of these are: (*a*) sandstone, shales, etc.; (*b*) rock-salt, gypsum, cave deposits (stalactites), etc.; (*c*) coral and shell limestones, chalk, guano beds, coal. The three groups here indicated are commonly made subdivisions of the sedimentary rocks, and designated respectively as follows: (*a*) mechanical sediments, (*b*) chemical sediments, and (*c*) organic sediments.

3. *Metamorphic Rocks.* These rocks were originally members of one or the other of the preceeding divisions, but have become sufficiently altered by natural agencies, such as pressure, heat, and so forth, so that for the most part the original characters are obliterated or lost, and new and special characters are added. Examples of such metamorphic rocks are: (*a*) *gneiss* — which may be derived from an original granite, but may also have originated from another rock, even from a sediment; (*b*) *mica schist*, which may have been derived from a shale or an impure sandstone or some other rock; (*c*) *marble*, which is derived from some form of limestone that may have been of organic, of chemical, or of mechanical origin; (*d*) *graphite*, which may be derived from coal beds or from carbonaceous shales, etc.

Such a classification is sufficiently serviceable for all practical purposes, but it cannot be called a scientific classification, because in the second and third group are included types of very diverse origin; for the three groups mentioned under sedimentary rocks have little or nothing in common, except that they are sediments in a very broad and indefinite comprehension of that term. More correctly speaking, they are not igneous rocks, and not pronouncedly metamorphic rocks, and this is almost their only claim to a grouping under a separate division. The metamorphic group,

too, includes, as we have seen, rocks of very diverse origin, but since it is not as a rule possible to determine, except perhaps after prolonged and careful study and analysis, if then, what the character of the original rock was, it will probably always be necessary to retain this group as a matter of convenience.

Principles of a Natural or Genetic Classification of Rocks

While the practical worker may find the preceding classification sufficient for all needs, and while in the succeeding chapters we may frequently refer to these convenient three types, the student should nevertheless understand the principles of a natural classification, and so far as it is practicable we shall base our subsequent discussions upon such a natural classification. For in geology as in other sciences, logical thinking is of the first importance, and logical thought is best fostered by the most rigid adherence to exact methods of classification, and the only exact classification of natural objects is one based upon genetic relationship, that is, upon community of origin of the members of each group.

At the outset of our endeavor to understand the natural relations of rocks we must clearly comprehend two fundamental principles. The first of these is, that in this natural world of ours all things are subject to continued change, even though that change may be a very slow one, so slow that the years of a man's life or those of many successive generations are of insufficient length to permit the recognition of such changes. All rocks are constantly undergoing modification, and though sometimes these changes may be rapid, as in the coking of coal in a burning mine, or the change of clay to brick in a kiln, the more usual method of change is a slow and gradual one. In a certain sense all rocks may be considered as *metamorphic* or altered rocks, a view strongly held by some geologists. Extreme metamorphism, such as produced the common types which are usually spoken of as metamorphic rocks, is only a phase of the general alteration or metamorphism which all rocks undergo, and this phase is characterized by the greater or complete obliteration of the characters which the rock possessed during its early history. This more pronounced change may have been brought about by the greater intensity of the activities responsible for it, or by their longer continuance in time, or by both.

The second principle, a knowledge of which is fundamental to our understanding of rocks as well as all other natural objects,

is that related types are not separated as a rule by sharp lines of demarcation, but that always and everywhere in nature gradation is the predominant rule.

Thus a sandstone may grade into a shale, on the one hand, and into a limestone on the other, and shale and limestone may intergrade, though of course there are always types which retain the characters of one or the other with sufficient distinctness to make their classification possible. A granite may grade into a syenite, and this into a diorite; and again, a granite and a diorite may approach each other so closely in character that classification becomes difficult. In like manner a sandstone may have so many characters of a schist that it becomes a difficult question to which of the two divisions it belongs. A shale may grade into a slate and a granite into a gneiss. With slightly metamorphosed rocks, classification is often very difficult, though a thoroughly metamorphosed rock is easily recognized as such.

Extreme metamorphism is only a later or final phase of the change which all rocks are undergoing, and in a natural classification such end-products are to be placed with the group from which they are derived. Two gneisses, for example, one of which is derived from a granite and one from some type of sandstone, are not related to each other any more than two human beings are related because they speak the same language, or obey the same laws of civilization. As before said, however, the practical difficulty of determining the original character of a metamorphic rock must be reckoned with, just as in the study of thoroughly civilized human beings of different but entirely disguised nationalities, the practical difficulty of ascertaining the nationality of each (assuming that the individuals refuse or are unable to disclose it) must be taken into account. In this respect thoroughly metamorphosed rocks hold the same relation to their ancestral type, as thoroughly Americanized individuals descended from different nationalities hold to their ancestors.

It thus becomes necessary for us to study first the unaltered or but slightly altered rocks, the history of which is ascertainable from the characters which they retain.

The Unaltered or Little Altered Rocks

When we study the unaltered or slightly altered rocks, we again note that they fall into two quite readily recognizable divisions. The first of these comprises rocks which have been produced from material not originally rock, — for example, by cooling from a lava,

crystallizing from a solution in water, and the like, — a group which in a broad sense may be spoken of as produced in a chemical manner. The other division comprises rocks which are made up of fragments or particles of other rocks, such as sandstone made of grains of sand, a conglomerate made of pebbles of various kinds and of sand, and others like these. This is the group of fragmental or *clastic rocks* (Latin: *clastus*, broken) which are always made from some preëxisting rock that has been broken down into discrete particles, which then are recombined either directly or after more or less assorting. The first group, on the other hand, is that of the non-fragmental or non-clastic type, which is not formed from fragments of other rocks, but from non-rock material. In the regular order of formation this type would appear first, though it is perfectly possible that non-fragmental rocks may originate from material which itself was derived from other rock, by melting, solution, or vaporization of such a rock and subsequent resolidification. But in this case there is an intermediate non-rock stage, while the material of the fragmental or clastic rocks is always rock, though it may be broken into the finest particles. We shall consider the characteristics of each group briefly.

The Non-Fragmental Rocks
(Endogenetic Rocks)

The non-fragmental rocks may be properly regarded as contributions to the lithosphere from three of the other spheres; namely, the hydrosphere, the pyrosphere, and the atmosphere. This contribution may be direct, as in the case of the hardening of a lava from the pyrosphere, the separation out of salt from the water of the hydrosphere, by the concentration of that water or by chemical reactions, or the separation of snow or hail-stones by the solidification of the water vapor from the atmosphere. Each of these spheres may thus in a measure be credited with the generation of these respective rocks, and it is therefore possible to speak of these three types, respectively, as: *pyrogenic*, generated by the pyrosphere; *hydrogenic*, generated by the hydrosphere; and *atmogenic*, or generated by the atmosphere. Instead of these names we may of course speak of these deposits as of igneous, aqueous, and atmospheric origin, respectively, recognizing the fact that the rocks contributed by the atmosphere direct, that is, the snow and hail, are of an evanescent character.

In addition to these three types, — the direct contributions of three of the inorganic spheres to the lithosphere, — there is an indirect contribution of material from two of these spheres by the agency of organisms. Both animals and plants take lime from the sea-water to build their shells and other calcareous structures, and other organisms take silica from sea-water to build their hard parts. Deposits of such organically secreted lime and silica are very important in the construction of the lithosphere, and form, as a rule, readily recognizable types of rocks.

Again, carbon is taken by plants from the carbon dioxide of the atmosphere, and the plant tissues built up from it may often become compacted into beds of coal which form important members of the rock series of the lithosphere. Here again is an organically formed rock, the material of which is obtained from the atmosphere.

Such organically formed rocks are the contribution of the biosphere to the lithosphere, and in conformity with the method of designation which implies such a relation to that sphere, they may be called *biogenic* rocks.

We may then summarize in the following table these four fundamental types of non-clastic rocks, rocks which are produced essentially by chemical (including physiological) reactions from non-rock material. We term these rocks *endogenetic* because they are formed by forces in a measure inherent in the material of the spheres which produce them.

THE FOUR TYPES OF ENDOGENETIC (NON-CLASTIC) ROCKS

1. Pyrogenic or Igneous: Produced by the pyrosphere.
2. Hydrogenic or Aqueous: Produced by the hydrosphere.
3. Atmogenic or Atmospheric: Produced direct by the atmosphere.
4. Biogenic or Organic: Produced by the biosphere from material taken from the hydrosphere or atmosphere.

We may consider these rock types from another point of view. Were we to imagine the rock material of the earth deprived of its solid character, that which is essential to the constitution of a rock, we should have to think of it as existing in one or more of three possible forms.

1. It may be turned into a molten mass like lava, by the application of heat, and so constitute an *igneous magma*, in which all the minerals which go to the making of the rock would become as it were dissolved in one another, and the compounds dissociated into

their ions. It would then become a part of the pyrosphere, and in this state most of the rocks of the earth are believed to have existed at an earlier period according to the believers in one hypothesis of the earth's origin (see Chapter XXIX) when the earth as a whole was a molten mass. Whether this theory is correct or not, the fact that many of the rocks of the earth's crust were at one time in this state cannot be doubted. By solidification *igneous* or *pyrogenic* rocks are formed.

2. The rocks of the earth may be turned into a condition of vapor — by the application in most cases of still greater heat. In such a state they would become a part of the earth's atmosphere. The same hypothesis of earth-origin holds that this was a condition of the entire rock mass of the earth at a still earlier period, and that from this condition of vapor was separated at a later period the molten material of the earth, and later still the water of the hydrosphere. Again, the truth of this hypothesis is not essential to the recognition of the fact that some at least of the rocks of the earth were formerly in a condition of vapor, and that they were separated from the earth's atmosphere either by direct condensation, as we see to-day in the formation of snow, or by the work of organisms, such as has resulted in the separation of the carbon of the atmosphere, which now constitutes our coal beds, by the agency of plants. Rocks derived by direct condensation from the atmosphere are *atmogenic* rocks, while those separated by the activities (physiological) of organisms, are *biogenic* or organic rocks.

3. Finally, we may think of the rocks of the earth, or at least some of them, as dissolved in the universal fluid envelope of the earth — the water — and so become a part of the hydrosphere. If rock material, thus held in solution, is separated out from the water by direct condensation, by chemical reactions, or by electrolytic action, *aqueous* or *hydrogenic* rocks are produced. If, however, the dissolved material is separated out by the agency of organisms, as in the formation of limestone masses on coral reefs by polyps and lime-secreting seaweeds (algæ), it becomes an *organic* or *biogenic* rock.

There are no other primary states than those of fusion, solution in water, or vaporization, into which the rocks of the earth may be changed, nor are there any other known ways in which rocks are formed from the three states of primary dissociation except by direct precipitation or separation or by organic agencies. Hence

the four rock types — the igneous or pyrogenic, the aqueous or hydrogenic, the atmogenic, and the organic or biogenic — are the

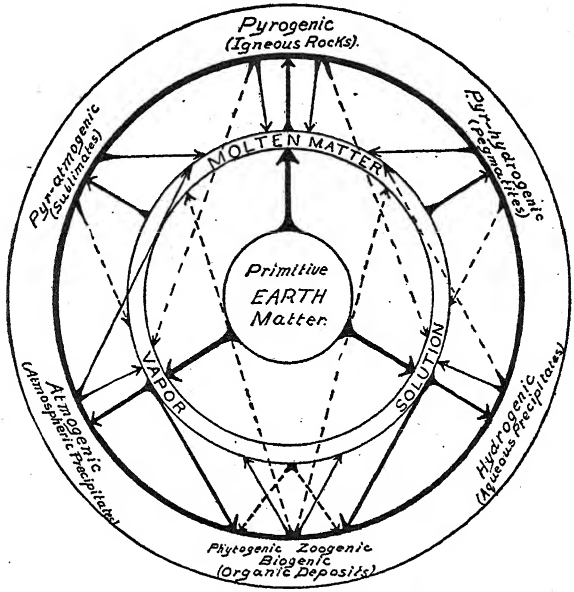


FIG. 27. — Diagram showing the interrelations of the Endogenetic Rocks.

only primary types recognized. These relationships are shown in the preceding diagram. (Fig. 27.)

The Fragmental or Clastic Rocks
(Exogenetic Rocks)

These are the rocks which are made up of fragments of other rocks, which may range in size from dust particles of microscopic dimensions to boulders many feet in diameter. For their production it is evident that preëxisting rocks should be broken into fragments, and that these fragments should become recemented or bound together again in some manner. The methods by which rocks are broken into fragments, and those by which the fragments are recemented will be taken up later, but we may here use as an illustration of this type of rock one of the artificial rock-making processes carried on by man, and which differs primarily from the natural process in the rapidity with which it is carried forward. This is the process of manufacture of rubble concrete for paving

and other construction. Rocks like the trap of the Palisades, an ancient igneous rock, are quarried and passed through the stone-crusher, where they are reduced to rock rubble or particles of small dimensions. They are assorted into different sizes by screening, and bound together by a cement, which is a mixture of lime, alumina, and silica, and of sand, which is the finer rock material obtained either from the screening, or more commonly from natural sand banks. The result is a clastic rock, but an artificial one, and this is produced in a few days, whereas a similar rock produced in nature might require as many centuries or millenniums for its production. But trap rocks or other igneous rocks are not the only ones used in the making of rubble concrete, nor are igneous rocks the only source of clastic material in nature, though they are often the most common one. All rocks, — igneous, aqueous, and organic, and clastic rocks as well, — are broken into fragments by natural agencies, and from these fragments new clastic rocks are made. For the rocks of the earth's crust are being constantly reworked, all of them, whether clastic or non-clastic, furnishing material for the formation of a younger bed of clastic rock. Let us take an example for illustration from the eastern United States.

There is in the foothills of the Catskill Mountains a great deposit of bedded clastic rocks known to the arts as Hudson River Blue Stone, and used for the manufacture of flag-stones for sidewalks in New York City and elsewhere, for curbings, and for many other purposes. To the geologist this rock is known as a member of the Middle and Upper Devonian series of rocks, of which we shall learn more in the future. Examination under the microscope shows that this rock is composed of small particles, some of which are themselves small fragments of clastic rocks (these are called *clastoliths*) and this shows that this particular blue-stone rock is made up of material derived in large part, if not wholly, from an older clastic rock which was broken into fragments, assorted according to size by natural agencies, and recemented to form new clastic rocks, the " Blue Stone " being made up of the assorted finer particles only. From the character of the small fragments of clastic rock (the clastoliths), and from a study of the structural and age relations of the " Blue Stone " to the rocks of greater age, it has been possible to determine that the material of the " Blue Stone " was derived from the so-called Hudson River formation, which crops out to the east of the Blue Stone area and forms in part the Taconic

Mountain range along the New York-Massachusetts boundary line. This rock is of much greater age than the "Blue Stone," belonging to the Ordovician period of the geological series (see table, Chapter XXIV). Similar examination of this Ordovician clastic rock shows that it in turn was derived from a still older clastic rock, this time of Pre-Cambrian age, some of which can be seen in the ledges of Manhattan Island. This clastic rock finally was derived from still older igneous and metamorphic rocks (Berkey).

A second example from the central region of our country may be given. In Ohio, Michigan, and Western Ontario is a great bed of very pure sandstone, a clastic rock made up almost entirely of small, well-rounded grains of quartz sand bound together. This rock is so pure that it is used for glass-making in Toledo, Ohio. It is known by the name of the *Sylvania sandstone*, and it belongs to the Silurian division of the geological series. Careful study has shown that the grains were originally a part of a still older sandstone, called the Saint Peter sandstone, which belongs to the Ordovician division and covers a large area in the Mississippi Valley region and east of that in Michigan, Canada, etc., though its outcrops are found only in restricted areas. This rock was in turn derived, at least in part, from the destruction of a still older sandstone, the so-called Potsdam sandstone of Cambrian age, which crops out farther to the north, in Wisconsin, Minnesota, etc. This sandstone finally was derived from the still older granites, gneisses, etc., which are seen in the Canadian region to the north. Thus the Sylvania represents the third generation of sandstone, the Saint Peter the second, and the Potsdam the first.

Finally we may note that the modern sands of the Libyan desert are derived from the breaking up into its component grains of an older sandstone, the Nubian, and of the rock from which the sphinx has been cut (Fig. 28). If these sands become bound together into a sandstone at some future time, this sandstone will be of the second generation.

We see, therefore, that clastic rocks may be of different generations. The first generation is always derived from some igneous or other non-clastic rock or the metamorphosed product of such a rock. The later generations are derived successively from older clastics, though new contributions from the crystalline source may also be made. This formation of a new and younger clastic rock from the material of an older one may be compared with the

construction, in more recent times, of man-made structures and monuments from the stones obtained by the demolition of older human monuments or structures.

The cycle of change which includes the successive generations of a clastic series may be brought to an end by the melting of the

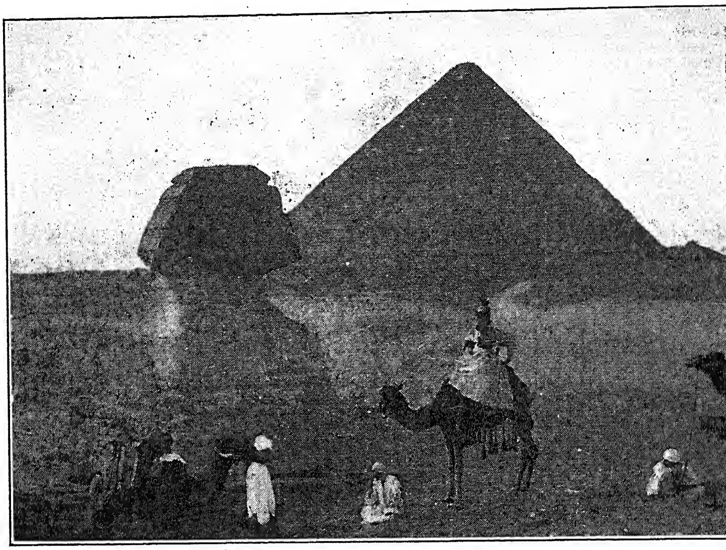


FIG. 28.—The Sphinx, cut from a rock ledge and surrounded (and formerly partly buried) by desert sands derived largely from the destruction of a sandstone in other parts of the Libyan desert. The Great Pyramid in the background is covered by slabs of Nummulitic limestone.

clastics, and by their incorporation into a new igneous mass, or by their pronounced metamorphism. Then a new cycle of formation of clastic rock will begin.

The Agents Active in the Breaking Up or "Clastation" of Rocks

We may now consider the chief agents which are active in the breaking up or clastation of rocks, that is, those responsible for the formation of clastic material from which clastic rocks are formed by consolidation. We may classify the several types of clastic rocks according to the agent which produces the material, or which arranges it in the form in which it becomes consolidated. The methods of clastation will be considered in a later chapter.

The Atmosphere as a Rock Breaker. — In the first place, rocks are broken up or "clastated" by the atmosphere acting either chemically, by the action of the various gases and vapors of the air upon the rock, or mechanically, as in the case of freezing moisture, or by the wind. Clastic material thus produced may be called *atmoclastic* material, and rocks formed by the consolidation of such clastic material may be called *atmoclastic rocks*. As clastic material is often accumulated in certain localities after transportation by the wind, *i.e.*, the atmosphere in motion, and as this material has generally a very definite form and structure, we may further distinguish wind-arranged or wind-deposited clastic material, such as is found in sand-dunes. When this is consolidated into a rock it becomes a wind-formed or *eolian* rock, a rock which may also be called *anemoclastic* from the Greek *anemos* (ἄνεμος), the wind.[1] There are many examples of such wind-formed, eolian, or anemoclastic rocks to which we shall call attention again in a later chapter. We may mention here as examples the recent dune-rock of the Bermuda Islands, and the much older sandstones of the White Cliffs in the Colorado Plateau region. The first of these was formed in the modern or *Holocene* period, the second in the *Jurassic* period, and this has retained its structure ever since that time, though much of the original rock, which had a far wider distribution, has been worn away again from large areas.

The Hydrosphere as a Rock Breaker. — The second great agent which accomplishes the destruction of rocks is the hydrosphere. This destruction, so far as it bears on our present point of view, is mechanical in its nature, although chemical work, the solution of rocks (such as limestone, salt, etc.) is also performed by the hydrosphere. Such solution, however, results in the reincorporation of the rock material into the material of the *hydrosphere* from which in turn it may be deposited as an aqueous or hydrogenic rock (stalactites and other cave deposits). Such a rock is, however, not a clastic but a "genic" rock, and the student should learn to make the proper distinction between these two.

The mechanical work of water is manifested in streams, where the current moves the rock fragments which it has broken from the ledges, and grinds them down as it carries them along. It is also seen on the seashore, where the waves produce an analogous effect.

[1] We have this same root in the word *Anemone*, the name of the wind-flower, in *anemometer*, the instrument for measuring the velocity of the wind, etc.

But in addition to the breaking off of the rock fragments and the grinding of them to sand and pebbles, moving water in streams and on the sea-coast assorts clastic material, however produced, into grades of various sizes, and more or less according to the weight, and therefore the nature, of the material. Moreover, clastic material deposited by and in the water will generally be char-

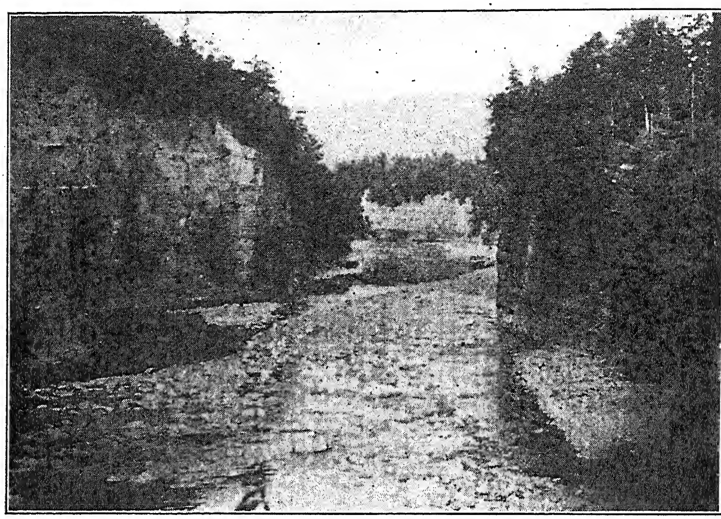


FIG. 29. — Gorge of the Genesee River below the Lower Falls at Portage, N.Y., showing in the opposite banks, the cut edges of the stratified rocks (shales and sandstones) which formerly were continuous across the gorge.

acterized by a bedded structure; that is, it will exhibit, if seen in section, a succession of layers or strata one above the other, each one of which was at one time the topmost layer (Fig. 30). Such deposits are called *stratified*, and of course, at any one time, only the top of the topmost *stratum* is visible. Where a river, however, has cut a gorge into an older stratified series, or where the waves on the sea-coast or lake shore again partly wear away such a series which has been lifted above the level of the sea by natural disturbances, or rises above the lake-level, the cut edges of such strata can be seen. Thus on the opposite banks of the Genesee River (Fig. 29) we see the cut edges of the successive strata which were formerly continuous across the chasm. On the sea-coast at Atlantic Highlands, N.J., we likewise see the edges of the strata which were exposed because the waves cut laterally into the old deposit which

had been previously uplifted; and a similar exposure of successive strata is seen on the shore of Lake Erie (Fig. 16, p. 31) and on many other shores (Fig. 30).

In addition to the bedded structure called *stratification*, which is characteristic of water-laid deposits of clastic material (and to some extent of hydrogenic deposits also), there are other features

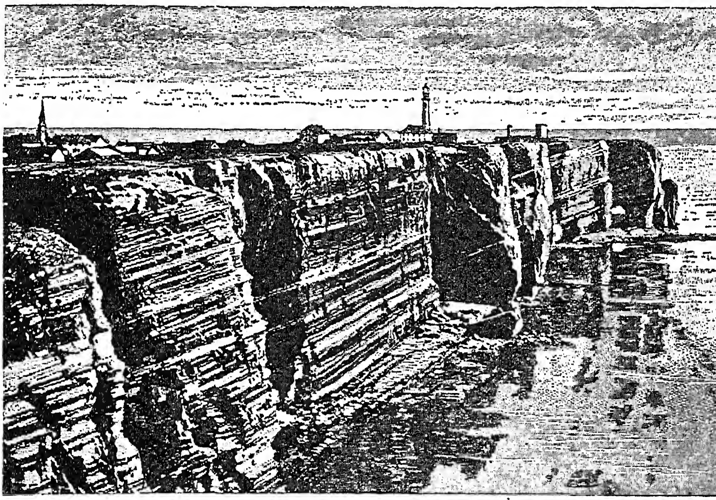


FIG. 30. — Sea cliff of the south coast of Helgoland, showing the edges of the stratified rocks of which the island is composed, exposed by wave cutting. The strata are of Permian age and dip towards the north, but appear to be horizontal in the sea cliff. (After E. Haase, from Walther.)

by which water-laid clastics may be recognized. These will be more fully discussed in a later chapter. At present it is merely desired that the student should recognize that water-laid deposits have definite characters. Some of these may point to a deposition of the material on a river flood-plain, an alluvial fan, or a delta; some to deposition in lakes, ponds, or playa basins, and some to deposition in the sea. These last may be regarded as the most typical examples of water-laid clastics, and they are generally characterized by the inclusion of the shells and other remains of marine organisms. A sandstone or mud-rock with marine fossils (Fig. 31), such as may be obtained from numerous localities the world over, will serve as a typical example of a water-laid clastic. In accordance with the general method of naming such deposits, those under consideration may be termed *hydroclastic*. They

may also be called *aqueous* clastics or sediments, in distinction from aqueous precipitates or concentrates, which belong to the group of hydrogenic deposits.

The Pyrosphere as a Rock Breaker. — As we have seen, the pyrosphere contributes pyrogenic or igneous material, which on

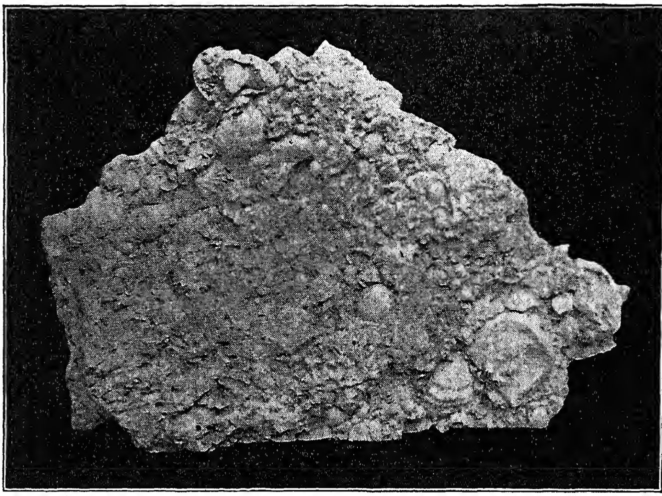


Fig. 31. — Photograph of a slab of sandstone filled with marine fossils. (Oriskany sandstone, N. Y.)

cooling and hardening forms a part of the solid crust of the earth. It also breaks up material already rock, and this is generally brought about by explosive activities such as are characteristic of most volcanoes. By these activities the rock, whether an older lava or a rock of other origin, located in and around the crater, may be shattered and the material thrown high into the air, to descend as a shower of ashes or larger particles. Such material, which is readily recognized by its character, is called *pyroclastic* material, and when bound together to form a rock, this becomes a pyroclastic rock. Examples: volcanic tuff, volcanic agglomerate, etc.

Fig. 32. — Fault-breccia.

Shattering of Rocks within the Lithosphere by Movements. — When one part of the lithosphere moves over or against another

part, as happens when the earth's crust suffers disturbances (see Chapter XXI) the rock along the plane of movement is shattered or ground fine, and clastic material with very definite characteristics is produced. As such a movement of adjoining rock masses generally produces a displacement, or fault (see Chapter XIX), the shattered or ground-up material is commonly called a fault-breccia (Fig. 32). A more general term for such material is *autoclastic*, because it is produced by the self-destruction or breaking up of the rocks of the earth's crust.

The Biosphere as a Rock Breaker. — That growing plants, such as trees, arising from seeds which lodged in a fissure of the rock, can by expansive growth shatter that rock, has been frequently observed (Fig. 33). Animals, too, break rocks. Thus where a spring issues upon a level surface in a more or less arid country, vast herds of hoofed animals will congregate to drink, and their constant stamping of the rock surface will break it and produce dust and sand which mingles with the water and which on drying may be carried away by the wind. Thus hollows are produced in the surface of the land, and these may be filled with water and so produce ponds.

Fig. 33. — A huge gravestone, broken and displaced by the growth of the roots of a birch-tree. Hannover. (After Walther.)

Many such are known to exist in western North America, in north and central Africa, and elsewhere. Fish and other animals in the sea will break off branches of coral from reefs (biogenic rock) and grind these to powder to obtain for nourishment the animal matter which surrounds these coral masses. Thus much coral sand and mud is produced, and this is clastic rock material of strictly organic origin.

But by far the greatest destroyer of rock is man. We have seen

how rock is broken down to be used for the making of artificial rock, that is man-made rock (rubble-concrete, etc.). As man is a part of the organic world or biosphere, his work must be classed with that of other organisms. Clastic material thus produced by organisms, and the rocks, whether natural or artificial (*i.e.*, man-made), made from these, may therefore be called *bioclastic.*

Summary of Clastic Rocks

We have thus five main groups or classes of clastic rocks, each produced by one of the spheres and named after it. (See the diagram, Fig. 34.) In general the rock is regarded as belonging to

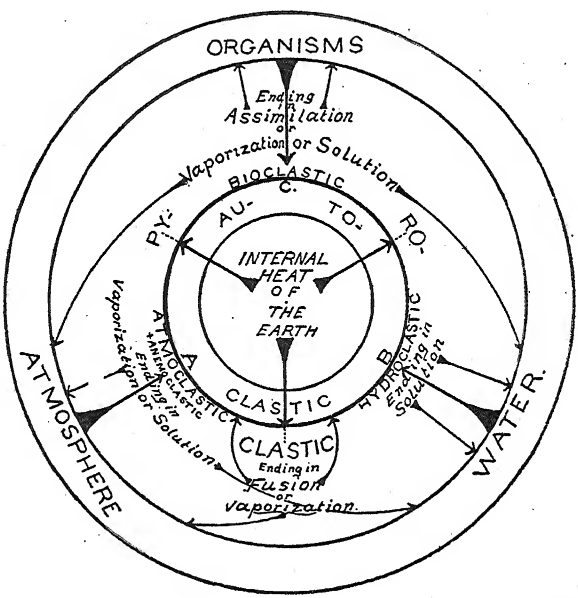


FIG. 34. — Diagram of the interrelations of the Exogenetic Rocks.

that particular class, the agent of which has placed upon it its characterization stamp. Thus the material of a water-laid rock may have been originally produced in another way than by aqueous erosion — it may have been produced by weathering, after which it was sorted by and deposited in the water. Thus water has stamped it as undeniably an aqueous clastic or hydroclastic rock. If it is possible, as it sometimes is, to determine how the material

originated before it was deposited by and in water, this may serve to further characterize the rock as of a special division in the hydroclastic group. The types of clastic rocks then are:

1. *Atmoclastic rocks.* Rocks produced by atmospheric destruction of rocks, and consolidated without rearrangement. Example: consolidated laterites.

1*a*. *Anemoclastic rocks.* Eolian rocks. Material of variable origin, transported, assorted, and deposited by wind. Example: eolian sandstone.

2. *Hydroclastic rocks.* Rocks produced from material eroded or sorted by, and deposited by and in water, whether by rivers (fluviatile) in lakes (lacustrine) or in the sea (marine). Examples: fossiliferous marine sandstones or shales.

3. *Pyroclastic rocks.* Rocks formed from material which has resulted from shattering of older rocks by volcanic explosions. Examples: volcanic tuff, volcanic agglomerate.

4. *Autoclastic rocks.* Rocks formed of material shattered or ground by movements within the earth's crust. Example: fault-breccia.

5. *Bioclastic rocks.* Rocks produced from material broken or arranged by animals (more rarely by plants) and by man. Includes artificial rocks. Examples: some consolidated muds from coral reefs, rubble-concrete, etc.

In the succeeding chapters we will consider first the commoner types of rocks, in which the original characters are retained, and their structures, leaving the metamorphic derivatives for a future chapter.

CHAPTER VI

THE PRINCIPAL TYPES OF IGNEOUS OR PYROGENIC ROCKS

The Igneous Magma

The term molten magma is applied to molten rock material or igneous fluid, which is formed or exists within that part of the earth which we have called the pyrosphere, and which, it will be remembered, interpenetrates the lithosphere and the asthenosphere (tectosphere). When the magma reaches the surface of the earth, either in a volcanic eruption, or through large fissures in the earth's crust, as in parts of Iceland to-day, it is called a *fluid lava*, from which by solidification in cooling a *solid lava* or lava-rock is produced. Such a rock mass constitutes an *extrusive* or *effusive* igneous rock mass. When the magma does not reach the surface, but cools within the crust of the earth, into which it has risen or become intruded to a greater or less extent, either upon or by the formation of fissures, or otherwise, it forms an *intrusive* igneous mass. Finally, a magma may be conceived as cooling essentially where it was formed, and to produce a *deep-seated* or *abyssal* igneous rock mass.

Outcrops of Igneous Rock Formed by Solidification from Magmas

It is obvious that only the surface-flows or lavas will be accessible to man immediately after cooling, and of these generally only the superficial portion. All the other igneous rock masses are located within the earth's crust, and buried beneath the surface rock masses, sometimes to very great depths. Some of those which closely approach the surface may be reached by deep borings or by mining operations, but this can occur only in exceptional cases. Some of these may also be conceived of as brought into view on the face of a great dislocation-block of the earth's crust, where one side of the broken crust is lifted and the other depressed. This too,

however, is probably so exceptional that it may be considered, in the absence of other modifications, to be practically negligible. In general, it is only after prolonged erosion, which results in the removal of much of the surface-covering of the rock, that intrusive masses become exposed, while deep-seated masses may require the removal of many thousands of feet of covering rock before they become visible. This removal of great covering rock masses requires, of course, long periods of time, and it thus becomes evident that the igneous rock masses, other than surface lavas, which are now visible in outcrops, are of great age, and that their formation by cooling has taken place at remote periods of time. Igneous intrusions and deep-seated masses which are now being formed are entirely invisible to us, and will not be exposed until many ages have passed by, if ever. Nevertheless there are indirect ways in which we can infer the existence of igneous masses beneath the surface, which are now undergoing the process of solidification, and to some of these we shall refer later.

Characters and Composition of Igneous Magmas

It is not possible to gain a complete knowledge of the composition of an igneous magma from the composition of the igneous rock which has resulted by solidification from that magma, because the magma contains in addition to the substances which make up the solid rock formed from it, large quantities of volatile gases which are expelled upon cooling and relief of pressure. The volatile gases which are expelled under these conditions are, water vapor, carbon dioxide, hydrochloric acid, sulphurous vapors, and the like. Such expulsion of volatile matter is shown by all surface lavas from which clouds of steam arise, and such steam on analysis proves to carry with it many of the other gaseous emanations. Others quickly condense upon the surface and may form salts of various kinds, which either encrust the surface of the cooling lava, or are carried away in solution by the condensing waters from the water vapors. Sometimes the expulsion of gas and vapors is so rapid that violent explosions result, and this is indeed the chief cause in the production of pyroclastic material. In practically every volcanic eruption there is produced a cloud of vapor and gases which carries upward vast masses of finely divided rock material — the product of the explosive action — and often rises

to heights of many miles above the volcano (Fig. 35). When gases and vapors alone issue from a fissure in the earth, the phenomenon is spoken of as a *fumarole*. Fumaroles are commonly associated with declining volcanic activities. The gases and waters of cooling magmas within the earth's crust may escape through fissures not penetrated by the magma or opened since cooling began, and these may reach the surface as mineral springs, either hot or cold. In their upward passage, such waters and gases may deposit mineral matter which they carried, and this is believed by many to account for vein and other mineral deposits.

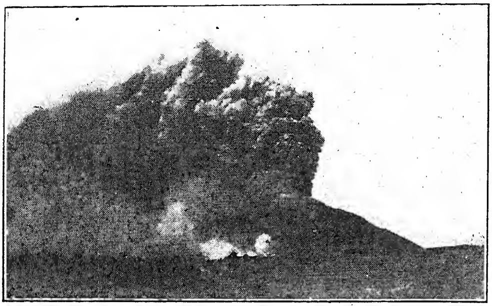


FIG. 35. — Volcano in eruption, showing the cloud of steam and ashes projected high into the air.

The non-volatile material of the magma which solidifies to form the lava or other igneous rocks consists predominantly of only a small number of substances, chief among which is silica (SiO_2), which, however, is present in variable amounts, according to the nature of the magma. In addition to this there are the oxides of the metals aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na), and potassium (K). These, too, vary in amounts in the different magmas. On solidification the silica unites with them to form various *silicate* minerals, which in the coarser-grained igneous rocks can be readily distinguished.

In a general way there can be recognized a gradation in the composition of the magmas from a point where silica is most abundant, sometimes forming 75 per cent of the whole mass, with alumina and potassium next, by an increase in sodium and later in calcium, magnesium, and iron, and a reduction in silica to a point where this constitutes 50 per cent or less (rarely 35 per cent) of the entire mass. With this occurs a reduction in the oxides of potassium, sodium, and aluminum, sometimes to the complete or nearly complete elimination of some of these. The end high in silica, etc., is called the *acid* end of the series; the other end is the *basic* end. Rocks formed from the acid portion of an igneous magma generally have

light-colored and light-weight minerals predominating; those formed from the basic portion have mainly dark-colored and heavy minerals. Acid magmas (and lavas) are generally very stiff or *viscous* even at high temperatures (2000° C. or over), and their contained gases escape with difficulty, and often with explosive violence, as the magma approaches the surface. Basic magmas (and lavas), on the other hand, are more fluid even at much lower temperatures (1300° C.), and on this account the gases escape more readily, and explosions are less common. The lavas of Vesuvius and Mont Pelée are examples of the first, those of Kilauea in Hawaii, of the second.

Formation of Igneous Rocks by Cooling of Magma

With the cooling of the non-volatile part of the magma, solidification takes place and igneous rocks are produced. The kind of rock will of course vary with the variation in the composition of the magma, which must be considered to be the character of first importance. Next to this is the rate of cooling, which determines the grain or texture of the rock, and which in turn is influenced by the relative position of the magma while cooling.

Influence of Rate of Cooling. Texture

It is a well-ascertained fact that a rapidly cooling magma will tend to produce a mass of glass, and that in proportion as the rate is slower will there be opportunity for the growth of mineral crystals, the size of which is, in general, proportional to the slowness of the cooling. When the entire rock becomes a mass of mineral crystals, it is said to be *holocrystalline*. Between this and the *glassy* type in which there are no crystals, there are all gradations. The relative size and arrangement of the component crystals of a rock form its *texture*.

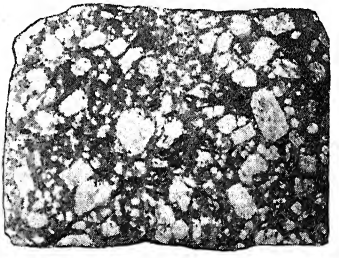


Fig. 36. — Porphyry; typical porphyritic texture.

Primary Textures. — Two general types of primary texture may be distinguished, the *homogeneous* or *uniform*, and the *heterogeneous* or *porphyritic*. In the first all the crystals of each mineral

are essentially of uniform size, though the size varies with the mineral. In the second, or *porphyritic* type (Fig. 36), on the other hand, the crystals of certain of the essential minerals (generally the feldspars) are of two sizes, one large and more or less fully and perfectly formed, the other small and less perfect. The larger crystals, which are scattered through the mass, are called the *phenocrysts;* the finer-grained mass, together with other minerals, also in small grains, forms the *ground-mass.*

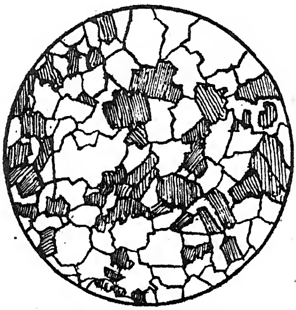


FIG. 37. — Granitic texture (holocrystalline), slightly enlarged.

Secondary Textures. — The textures of the ground-mass and of the homogeneous textured rocks are called secondary. When the grains or crystals are all nearly uniform, the texture is said to be *granitic* or *granular* (Fig. 37), and it may be coarsely or finely *granular, i.e.*, the texture is *coarse-grained* or *fine-grained* so long as the individual crystals are distinguishable. But when the crystals are no longer distinguishable, the texture becomes *dense* or *felsitic,* while a step further brings us to the *glassy* texture in which no crystals are developed.

Relation of Textures to Kinds of Magmas

In general, the basic magmas, being more fluid, will tend to form coarser crystals, the resulting rocks therefore being more commonly coarse-grained. Glassy textures are correspondingly less frequently developed. Acid magmas, on the other hand, tend to develop the finer textures more frequently, and here glassy rocks are common.

The presence of much gas and water vapor, too, tends to increase the power of crystal forming, and along certain fissures, presumably the pathway of escape of these gases and vapors, the texture is often of exceeding coarseness. The most common examples are the dikes or other masses of *pegmatite*, a rock composed sometimes of huge crystals of feldspar, quartz, and mica, the latter mineral being obtained in large plates from this rock, which is the chief commercial source of this mineral.

Relation of Texture to Place of Cooling and Bulk of Magma

As the coarseness of grain is in proportion to the slowness of cooling, it is evident that, other things being equal, whatever lowers the rate of cooling will cause an increase in the size of the crystals, and of the coarseness of texture. Thus a magma cooling within the earth's crust, especially at great depth, will of necessity cool slowly, and so become a coarsely crystalline rock. Again, the central part of the magma will cool more slowly than its outer part, which is in contact with the cooler enclosing rock. In like manner small masses will cool more rapidly than large ones, and this is especially the case when the igneous mass is a thin sheet transecting other and cooler rocks (dikes (Fig. 38), sills, etc., see beyond). There is, however, one modification of this general rule, which should be noted, and that is the conditions under which porphyritic rocks appear. In these the fine ground-mass indicates rapid cooling, but the presence of the large phenocrysts shows that these crystals grew to their full size before the ground-mass solidified. In other words, the phenocrysts were floating crystals in a still semi-fluid matrix. Typical porphyries (Fig. 36) (with fine-grained ground-mass) are most common in certain lava flows (as in the typical trachyte from Drachenfels, Germany), somewhat less so in the smaller intrusive masses, and still less common, and indeed rather rare, in the great subterranean masses. All types of igneous rocks may, however, show a porphyritic texture.

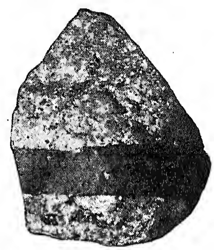


FIG. 38.—Small dike of basalt, showing dense texture, cutting syenite of finely granular texture.

Classification of Igneous Rocks

From what has been said up to this point, it appears that the principles which underlie the classification of igneous rock are relatively simple. The first general division is made upon a chemical basis, which in the rocks is expressed by the mineral species present. Further subdivisions are based upon the texture of the rock, for the same magma may furnish rocks of different textures as the result of cooling at different rates under different conditions.

Since, as above stated, the character of the magma is most readily ascertained from the minerals which crystallize from it, chief attention is ordinarily given to these minerals. Furthermore, since these are readily recognizable only in the coarse-grained or holocrystalline products of cooling of the magmas, it is customary to designate the rock groups based on chemical and mineralogical characters by the name of the typical holocrystalline member of each group. Before we consider these types, however, we must briefly review the essential minerals which enter into the construction of these rocks.

The Essential Minerals of Igneous Rocks

We may in general distinguish three groups of essential minerals which make up the bulk of the igneous rocks. These are the following, arranged in each case in the order from acidic to basic. They are: (1) Quartz, (2) The Feldspars and Feldspathoids, and (3) the Micas and Ferro-Magnesian Silicates.

Quartz (SiO_2). — This generally occurs in glassy fragments of irregular and usually of angular form, more rarely in crystals. It is easily recognized by its hardness (see pp. 49 and 61).

The Feldspars. — In composition these are all double silicates of aluminum and an alkali metal (K,Na, etc.) or an alkaline earth (Ca,Mg, etc.) or both. In general the feldspars are divided into *orthoclase*[1] or the feldspar with right-angled cleavage, and *plagioclase* or the feldspar with oblique cleavages. The most acid feldspar contains only potassium in addition to both alumina and silicic acid (potash feldspar or orthoclase), the most basic only lime in place of the potash (lime feldspar or anorthite). Between the two stands the soda feldspar (albite) where sodium is the metallic base besides aluminum. Between the pure soda and the pure lime feldspars are a number of intermediate types, consisting of different proportions of both soda and lime; and between the pure potash and soda feldspars there are also mixtures of the two.

These relations may be expressed in the following table, where the three main or (theoretically) pure types of feldspars are each expressed by a molecular symbol and the mixed types by formulæ which indicate the proportions of each.

[1] *Microline* is a potash feldspar like orthoclase, but crystallizing in the triclinic system, and therefore of the *plagioclase* type.

Table of the Feldspars

		Principal or Pure Types	Mixed Types	Composition (Chemical Formula)	Composition (Molecular Symbol or Formula)
Orthoclase (Monoclinic)	Acidic Series	*Orthoclase* (Potash Feldspar)		$K_2O \cdot Al_2O_3 \cdot 6\ SiO_2$ or $KAlSi_3O_8$	*Or*
Plagioclases (Triclinic)	Acidic Series		Anorthoclase		Or_1Ab_2 to $Or_1Ab_{4.5}$
Plagioclases (Triclinic)	Acidic Series	*Albite* (Soda Feldspar)		$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$ or $NaAlSi_3O_8$	*Ab* to (Ab_8An_1)
Plagioclases (Triclinic)	Acidic Series		Oligoclase		Ab_6An_1 to Ab_2An_1
Plagioclases (Triclinic)	Acidic Series		(Andesine)		Ab_3An_2 to Ab_4An_3
Plagioclases (Triclinic)	Basic Series		Labradorite		Ab_1An_1 to Ab_1An_2
Plagioclases (Triclinic)	Basic Series		Bytownite		Ab_1An_3 to Ab_1An_6
Plagioclases (Triclinic)	Basic Series	*Anorthite* (Lime Feldspar)		$CaO \cdot Al_2O_3 \cdot 2\ SiO_2$ or $CaAl_2Si_2O_8$	*An* to (An_8Ab_1)

In ordinary rock determination it is very difficult to recognize the intermediate feldspars, though this may be done with more or less precision when a thin slice of the rock is placed under the microscope, and examined by the use of polarized light. From chemical analysis, however, which gives the amount of each substance present, it is possible to calculate the types of feldspar (and other minerals) present in the rock, a calculation which must, of course, be checked by microscopic examination. The plagioclase feldspars usually show fine parallel (twinning) striæ on some faces.

In general, it may be said that orthoclase, albite, and oligoclase are characteristic of acidic rocks, or rocks high in silica, with orthoclase in the most acidic, while labradorite, bytownite, and anorthite characterize the basic rocks, with the last at the most basic end of the series.

The Feldspathoids. — Under this designation are placed double silicates of aluminum and the alkalies or alkaline earths, which have many characters in common with the feldspars besides the general similarity in their composition, but differ in crystal form and some other characters. Theoretically we again have three types, the potash, soda, and lime feldspathoids, but actually the first two are more commonly intermixtures. This is shown in the following table. In the order of their importance as rock constituents, these minerals are *nephelite*, *leucite*, and *melilite*, the last being very rare.

Table of the Feldspathoids

Mineral	Composition (pure)	Usual Modification
Leucite	$K_2O \cdot Al_2O_3 \cdot 4\ SiO_2$ or $KALSi_2O_6$	Some Na_2O replaces part of K_2O
Nephelite	$4\ Na_2O \cdot 4\ Al_2O_3 \cdot 9\ SiO_2$ or (almost) $NaAlSiO_4$	Some K_2O and CaO replaces part of Na_2O
Melilite	$12\ CaO \cdot 2\ Al_2O_3 \cdot 9\ SiO_2$ or $Ca_3Al(SiO_4)_3$	

In general, the occurrence of leucite in igneous rock implies a magma rich in potash; nephelite, one rich in alumina and soda; and melilite, one poor in silica and alumina but rich in lime. Melilite occurs mainly in a few rare basalts.

Common Mica and the Ferromagnesian Minerals. — The name ferromagnesian silicates is given to the minerals (usually dark in color) which include in their composition both iron and magnesium. They comprise the dark mica, *biotite*, the *hornblendes*, *pyroxenes*, and *olivine*. The common or white mica (*muscovite*) has neither iron nor magnesium, but is a silicate of potassium and aluminum

together with some hydrogen. Its usual formula is $K(OH) \cdot Al_2O_3 \cdot 2SiO_2$, or $HKAl_2Si_2O_8$ and it is commonly called the potash mica. As might be inferred, it occurs in rocks where other potash minerals are common, such as granites, pegmatites, etc. It is also common in metamorphic schists.

In the ferromagnesian silicates we trace a gradation in composition from biotite, or black mica, in which potash is present, through the amphiboles and pyroxenes, in which the potash is replaced by lime, to olivine, where no alkali or alkaline earth is present. This is shown in the following table where muscovite is also placed at the acidic end and magnetite, the pure iron oxide, at the basic end.

Table of the Ferromagnesian Minerals and Their Two End Members

MINERALS	COMPOSITION	USUAL MODIFICATION
Muscovite	$H_2KAl_3(SiO_4)_3$ to $(HK)Al_2(SiO_4)_2$	Without iron or magnesium.
Biotite	$(HK)_2(MgFe)_2Al_2(SiO_4)_3$ (nearly)	Addition of magnesium and iron; reduction of alumina and silica.
Amphibole (Hornblende)	$Ca(MgFe)_3(SiO_3)_4$ (in general)	Substitution of calcium for hydrogen, potassium, and aluminum, though some of the last may be present.
Pyroxene (Augite)	$Ca(MgFe)(SiO_3)_4$ (in general)	
Olivine	$(MgFe)_2SiO_4$	Omission of calcium, some reduction of silica.
Magnetite	Fe_3O_4	Omission of silica and magnesium.

It must be understood that the amphiboles and pyroxenes are more complex in composition than here stated, and that there are a number of varieties of each, differing in composition. It is, however, not necessary that these be considered here. The common

amphiboles and pyroxenes crystallize in the monoclinic system, but there are also orthorhombic members of each group. The chief means of distinction is the (prismatic) cleavage form, that of the pyroxenes being nearly at right angles, and that of the amphiboles forming angles of nearly 120 and 60 degrees, respectively, as shown

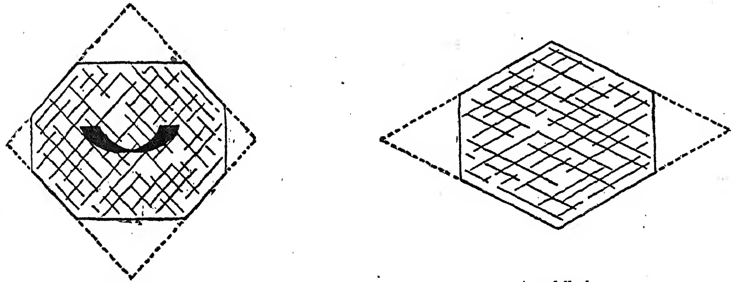


FIG. 39. — Basal sections of crystals of Pyroxene and Amphibole, showing characteristic differences in outline, and cleavage as seen under the microscope. A characteristic interference figure is shown in Pyroxene. (After Moses and Parsons.)

in the above outlines (Fig. 39). In general, it may be said that whereas muscovite occurs chiefly in the most acidic rocks, biotite and hornblende indicate greater basicity, pyroxenes still greater basicity, while olivine is characteristic only of the very basic igneous rocks. When pyroxene and olivine are present, free quartz is usually absent.

Secondary or Accessory Minerals. — There are many minerals which occur in small quantities in igneous rocks but are not necessary constituents of them. They are called accessory minerals, and their presence is most frequently detected by the microscope. Zircon and titanite are good examples of these. By alteration many other accessory minerals are formed from the primary or original ones.

Order of Crystallization

In general the order of crystallization of the minerals from an igneous magma follows the order of their basicity, the most basic separating out first, the most acid last. Thus olivine will form in perfect crystals from a basaltic magma; the other minerals being less perfectly crystallized. The pyroxenes and the hornblendes separate out before the feldspathoids and the feldspars, while

the quartz, if there is any free silica remaining, separates out last, filling the interstices between the other minerals. For that reason quartz is practically never in perfect crystal form in granites or other igneous rocks which contain it, but forms irregular grains, the shape of which is determined by the form of the cavities left between the other minerals. It has a crystalline structure, however, though not a crystal form.

Types of Igneous Rocks Based on Composition and Texture

The table on page 96 summarizes the more important types of igneous rocks, beginning with the most acidic on the left, and extending to the basic types on the right. It will be seen that there are certain composition groups based upon the kind of feldspar (or feldspathoid) present, the kind of ferromagnesian mineral, and the presence or absence of free quartz or olivine. Each of these composition groups includes a series of rocks ranging in texture from coarse (at the bottom) through fine and dense or felsitic to glassy (at the top). The coarser-grained rocks are generally formed as deep-seated masses, which have become exposed by erosion. The intermediate types occur mainly as intrusive masses, while the dense and glassy types (including the cellular) are primarily formed from surface flows. As the mineral character of the several groups is most readily ascertained in the case of the coarse-grained varieties, the various groups will be considered under these respective types. Microscopic examination is generally necessary to ascertain the characters of the finer-grained and dense types, though typical examples may generally be recognized without such aid.

The Granite-Rhyolite Series

This contains the most acidic of the common igneous rocks. Common types are: *granite*, *rhyolite*, *quartz-felsite*, *obsidian*, and *pumice*, and the porphyritic varieties of these.

Granite. — The coarse-grained members consist primarily of orthoclase feldspar and free quartz. When these alone are present, as is sometimes the case, the rock is called a *binary granite*. Generally, however, black mica (biotite) and often muscovite and some hornblende are present, these being readily recognized by their dark color, while the biotite is distinguished from the hornblende

Table of the Principal Igneous or Pyrogenic Rocks

(Modified after Kemp)

Ground Mass	Texture	Acidic Series			Intermediate Series		Basic and Ultra Basic Series					
Glassy	Porous or Cellular / Homogeneous	Pumice Perlite (pearl stone) Obsidian, Pitch stone			Andesite pumice Andesite perlite Andesite obsidian		Basic glassy scorias, Pele's Hair Tachylites and Basaltic obsidians					
	Recognizable Minerals	Chief Feldspar Orthoclase			Chief Feldspar-Acid Plagioclase		Chief Feldspar-Basic Plagioclase		Feldspathoids Nephelite-Leucite		No Feldspars	
		Biotite (or) (and) Hornblende more rarely Augite			Biotite (or) (and) Hornblende sometimes with Augite		Chiefly Pyroxenes no quartz		Pyroxenes		Augite (or) (and) Hornblende (or) (and) Biotite	
		With Quartz	Without Quartz	With Nephelite or Leucite	With Quartz	Without Quartz	Without Olivine	With Olivine	Without Olivine	With Olivine	Without Olivine	With Olivine
Dense or Felsitic	Non-porphyritic	Quartz felsite	Felsite	Phonolite felsite	Dark compact felsitic rocks		Various types of Basalts, Trap rocks, etc., of dense texture					
	Porphyritic	Quartz felsite-porphyry	Felsite-porphyry									
Finely Granular Acicular, etc.	Non-porphyritic	Rhyolite	Trachyte	Phonolite	Dacite	Andesite	Augite-andesite (Diabase)	Basalt (Diabase)	Rare basic basaltic rocks with nephelite and with leucite		Augitite	Limburgite
	Porphyritic	Porphyritic rhyolite Rhyolite-porphyry Granite-porphyry	Porphyritic trachyte Trachyte-porphyry Syenite-porphyry	Porphyritic phonolite Phonolite-porphyry Nephelite-Syenite-porphyry	Porphyritic dacite Dacite-porphyry Quartz-diorite-porphyry	Porphyritic andesite Andesite-porphyry Diorite-porphyry	Porphyritic augite-andesite Augite-andesite-porphyry Gabbro-porphyry	Porphyritic basalt Basalt-porphyry Olivine-gabbro-porphyry			Porphyritic augitite Augitite-porphyry Pyroxenite-porphyry	Porphyritic limburgite Limburgite-porphyry
Coarsely Granular	Non-porphyritic	Granite	Syenite	Nephelite-syenite	Quartz-Diorite	Diorite	Gabbro	Olivine gabbro	Gabbroitic rocks		Pyroxenite	Peridotite
	Porphyritic	Porphyritic granite	Porphyritic syenite		Porphyritic quartz-diorite	Porphyritic diorite	Prophyritic gabbro	Porphyritic olivine gabbro			Porphyritic pyroxenite	Porphyritic peridotite
Percentage of Silica (SiO_2)		80 – 65 %	65 – 55 %	60 – 50 %	70 – 60 %	65 – 50 %	65 – 50 %	55 – 45 %	50 – 40 %		55 – 30 %	

by its scaliness and softness. The orthoclase is commonly recognized by its pinkish or flesh color and by the smooth cleavage planes which it shows, as well as the more or less marked crystal form. The quartz is always in irregular, glassy masses, breaks with rough fracture and, as a result, looks darker than the feldspar by reflected light.

Granites vary by the replacement of some of the orthoclase by acid plagioclase while hornblende may increase in amount, forming a *hornblendic granite*. With this may go a reduction in the quantity of free quartz present, when the rock approaches a *syenite* in composition, while with the increase in plagioclase the quartz-diorites or diorites are approached. In rare cases, too, augite may occur, showing an approach to gabbro. Among the common accessory minerals are magnetite, zircon, and garnet. A porphyritic texture is sometimes developed by the formation of large and more or less perfect crystals of orthoclase, which frequently show a twinned character (Carlsbad twins), recognizable by the fact that one half of the crystal appears darker than the other in reflected light, the shade being reversed with change in the position of the light.

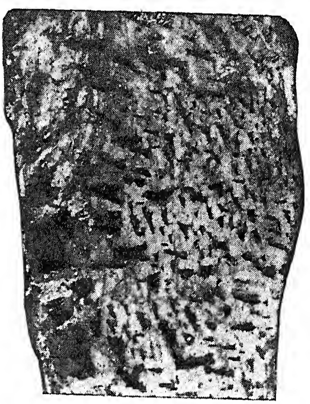


FIG. 40. — Graphic Granite, slightly reduced.

Pegmatite.—This is the name given to a coarse variety of a granite which occurs in vein or dike-like masses, and generally consists of large crystals of orthoclase (sometimes acid plagioclase) occasionally up to a foot or more in diameter, large masses of quartz, and large plates of mica (muscovite). The quartz and feldspar are sometimes found intergrown in such a manner that the surface of the feldspar seems to be scattered over with small, irregular, dark masses of quartz, appearing not unlike cuneiform characters. On this account such a mixture of feldspar and quartz is called *graphic granite* (Fig. 40).

Rhyolite and Quartz Felsites. — These have essentially the same mineralogical composition as granite, though the association may vary more, producing greater variety. In color the rocks are gen-

erally light gray, with yellows, and pale reds, and occasionally darker shades. The texture varies considerably, from very finely crystalline to dense or felsitic, when the rock consists of minute masses of quartz and feldspar often with more or less glass. A cellular structure may also be developed to a slight degree in rhyolites formed from surface flows. In many rhyolites, especially if they are porphyritic, quartz can be recognized (commonly as small double-sided pyramids), giving the surface a rough feel. Phenocrysts of feldspar also occur in the porphyritic types. When the phenocrysts of quartz and feldspar make up about half the mass of the rock it is called a *rhyolite-porphyry;* when it constitutes most of the rock it is called a *granite-porphyry* — and marks an approach to granite. In both the ground mass is generally dense or felsitic. The name rhyolite is given to this rock because of the flow structure often exhibited (Greek, ῥεῖν = flow).

The Acid Glasses. — These include obsidian, pitchstone, perlite, and pumice. In these the excess of silica, which on crystallization would produce free quartz, can generally be recognized only on analysis, except when phenocrysts are developed. As the magmas which produce syenites on crystallization also form glasses of similar appearance, though poorer in silica, it is evident that it is not possible to determine, except by analysis, whether a given glass belongs to that or to the granite series.

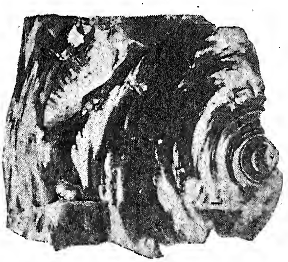


FIG. 41. — Obsidian, showing conchoidal fracture.

Obsidian. — This is a homogeneous glass with a low percentage of water. It is black to red in color, with translucent edges, and a conchoidal fracture, so called because the surface of the fracture is generally marked by a series of concentric lines, like the growth-lines of a shell (Fig. 41).

Pitchstone. — This is like obsidian, but contains from 5 to 10 per cent of water. It has commonly a sheen or luster suggestive of resin, and its colors are commonly reds and greens.

Perlite, or pearl stone (Fig. 42). — This is glass composed of numerous rounded masses, with concentric structure like the coats of an onion, formed by contraction in cooling and separated by larger straight cracks. It usually contains from 2 to 4 per cent of water.

Pumice (Fig. 43). — This is a cellular or porous glass, its character being due to the liberation of gases on cooling. It may be regarded as the consolidated surface froth of the lavas.

FIG. 42. — Perlite. Thin section under the microscope, enlarged 30 diameters. Hlinik, Hungary. (After Rosenbusch.)

All the glasses form from surface flows of lava, and the movement or flowing, after partial solidification, is commonly shown by the occurrence in them of layers of denser or more stony material, in which minute crystals of feldspar and quartz are developed. Often these are arranged in rosettes of radiating structure to which the name *spherulites* is given (Fig. 44). Cavities due to the expansion of steam or gases are also formed, which are generally spherical and often contain crystals of various minerals (topaz, quartz feldspar, garnet, etc.). These are called *lithophysæ* or stone bubbles (Fig. 45), and they vary in size up to an inch in diameter. Typical localities for obsidian are the Lipari Islands and Yellow-

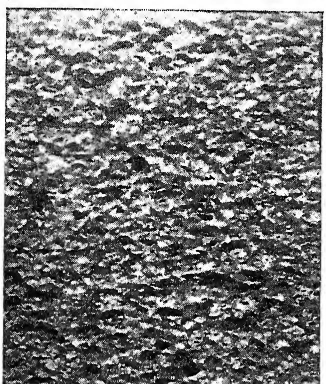


FIG. 43. — Pumice. Surface of a hand specimen.

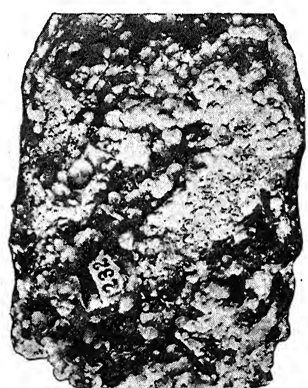


FIG. 44. — Spherulitic Obsidian.

stone Park; for pitchstone, Meissen near Dresden, Saxony, the Island of Arran, west Scotland, and Silver Cliff, Colorado; while the best known localities for perlites are in Hungary.

Devitrified Old Glasses. — Volcanic glasses of very early geological time have generally undergone a change by the development in them of excessively minute crystals of feldspar and quartz. From

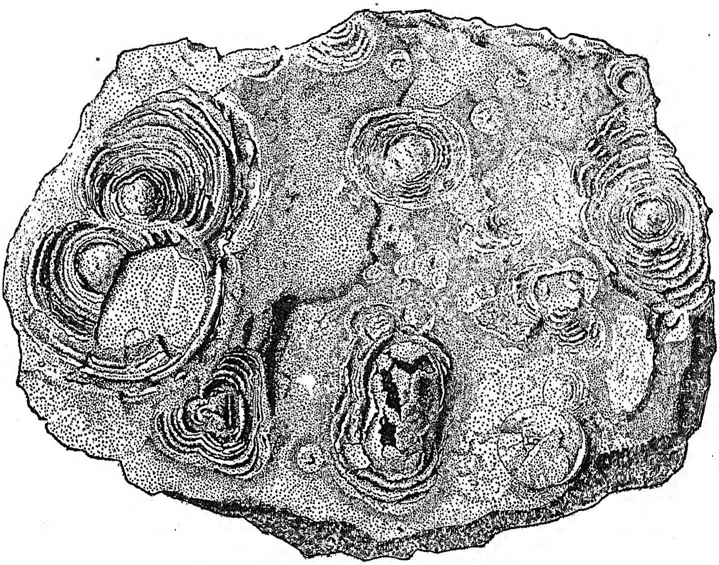


FIG. 45. — Lithophysæ in Lithoidite of Obsidian Cliff, Yellowstone National Park. Slightly reduced. U. S. Geol. Sur. Bull. 150.

this they lose their glassy appearance and resemble felsites, which name is commonly applied to them. They also have been called *petrosilex*. They are not uncommon in the old lava flows of the New England states and elsewhere.

The Syenite-Trachyte Series

This series is primarily characterized by deficiency in silica, so that no free quartz is formed on crystallization. It includes syenite, trachyte, felsites, and glasses.

Syenite. — This rock typically consists of orthoclase and hornblende, without quartz. When biotite is present, the rock is called *mica syenite*. In practically all syenites some of the orthoclase is replaced by plagioclase, and this may occur to such a degree that it makes up half of the feldspar, when the rock approaches a diorite, and is called a *monzonite*. Augite too may replace the hornblende, occurring with orthoclase and forming an *augite syenite*. Finally,

quartz syenite, with a small amount of free quartz, shows a transition from granites. With the appearance of nephelite, they pass into *nephelite syenites*. Porphyritic syenites have large crystals of feldspar. Common accessory minerals are magnetite, zircon, and apatite. The name syenite is derived from the ancient Syene (now Assuan) in Egypt, where the rock is, however, a hornblende granite which was formerly used for obelisks. As now used the name was first applied to a granite rock almost without quartz near Dresden (Plauen'sche Grund, or Plauen Gorge).

Trachytes and Felsites. — These have essentially the same composition as the syenites, of which they form the crypto-crystalline representatives with the same relationship that rhyolite holds to granite. Trachytes (Fig. 46) differ from rhyolites in the absence or great rarity of quartz. Biotite is in general the most abundant dark mineral, but hornblende and augite also occur, forming varieties. The texture varies from felsitic in the true felsites to strongly and coarsely porphyritic, and not infrequently the rock is somewhat cellular. Felsites, on account of their dense structure, cannot readily be distinguished from rocks of the same type in the granite or even in the diorite group. In typical trachytes, which are generally porphyritic, the ground-mass is made up of fine rods of orthoclase arranged more or less parallel and in flowing lines. This is the characteristic trachyte texture, which can often be seen with the naked eye in the coarser crystalline varieties. Large phenocrysts of a clear vitreous variety of orthoclase (called sanidine) are characteristic of the porphyritic trachytes.

When the phenocrysts are so abundant as to constitute about half the mass of the rock with felsitic ground-mass, it is called a *trachyte porphyry*. When phenocrysts form the bulk of the rock, while the ground-mass becomes more coarse-textured, the rock is called a *syenite porphyry* and marks the transition to syenite.

The name trachyte is derived from its rough or harsh surface feel (Greek, τραχύς, rough). The most typical trachytes come from the peak of the Drachenfels on the Rhine. (See map, Fig. 98.)

The Glasses of the Syenite Series. — Because the fusing point of these more basic rocks is lower than that of the granite series, being about 2000° F. (1100° C.) for trachytes as compared with about 2200° F. (1200° C.) for the rhyolites, and 2250° F. (1240° C.) for granites, they remain liquid longer, and hence crystallization occurs more generally with less frequent formation of glasses.

When glasses are formed, they are indistinguishable, except by analysis, from those of the granite series.

The Nephelite-Syenite Phonolite Series

These differ from syenites chemically in the greater amount of soda, and mineralogically in the partial substitution of nephelite (eleolite) for the feldspar.

Nephelite-Syenite. — This corresponds to syenite except for the presence of nephelite or sodalite, of both or of leucite. In some cases (Litchfield, Maine) the feldspar is wholly plagioclase. Zircon is a usual secondary mineral.

Phonolites. — (Klingstein, so called because of its ringing sound.) These rocks are generally dense and finely crystalline, seldom vesicular or glassy. They are mostly dull green or gray in color, and when light colored they are not readily distinguished from trachytes except by the microscope, which shows the presence of the nephelite. The chief feldspar is orthoclase, while the common dark mineral is augite, hornblende being rare. A peculiar character is the fact that the rock breaks into thin slabs which have a musical ring under the hammer. The rock is frequently porphyritic, both augite and feldspar phenocrysts appearing in a dense ground-mass. When the phenocrysts are very abundant the rock is called *phonolite-porphyry*, and when in excess, it becomes a *nephelite-syenite porphyry*. With increase in orthoclase and decrease in nephelite, the phonolites pass into trachytes. (See Fig. 46.)

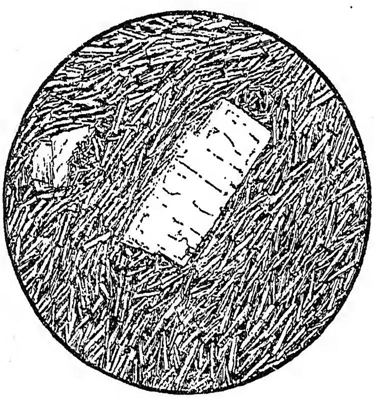


Fig. 46. — Trachyte-phonolite showing typical trachitic texture of the ground-mass and a large phenocryst. The Rhön, Germany. Enlarged 24 diameters, seen under crossed nicols. (After Rosenbusch.)

Glasses of the Nephelite-Syenite Series. — These are still rarer than those of the preceding case, since the fusing point of phonolites (somewhat less than 2000° F. or 1090° C.) is still lower than that of trachytes. Phonolite obsidians are known from the Peak of Teneriffe.

The Quartz-Diorite Dacite Series

The members of this series differ from those of the granite series, chiefly in the substitution of plagioclase for orthoclase. The plagioclase can be recognized by the striated character of the cleavage surface.

Quartz-Diorite. — This resembles granite, but is darker and heavier. Acid plagioclase, quartz, hornblende, and (or) biotite are the essential minerals. When biotite predominates the rock is called a *quartz-mica-diorite.* These rocks form a transition from granites to diorites, the intermediate forms being called *granodiorites.*

A typical locality for quartz-mica-diorite is found in the Cortland Series near Peekskill, N. Y., one for the hornblendic quartz-diorite in the Yellowstone Park.

Dacite. — This rock is difficult to distinguish from rhyolite except by the use of the microscope. It has the same relation to quartz-diorite that rhyolite has to granite. When the texture is finely felsitic and non-porphyritic, it can only be termed felsite. When porphyritic, the dacites are recognized by the striated surfaces of the plagioclase phenocrysts, which predominate. Glasses and cellular texture are not uncommon.

When phenocrysts constitute up to half the mass of the rock, it becomes a *dacite-porphyry.* When they are in marked excess over the ground-mass, it becomes a *quartz-diorite-porphyry.* The name is derived from the old province of Dacia, now Transylvania (Siebenbürgen), before the war a part of Hungary, which is a typical locality. Dacites generally occur with andesites.

Glasses of this Series. — The glasses of this series are more common than those of the syenite series, for the fusing point is only a little less than that of the granite series. They are generally included with the glasses of the next series.

The Diorite-Andesite Series

This differs from the preceding in the absence of free quartz (in the crystalline members) and from the syenite series in the substitution of acid plagioclase for orthoclase.

Diorites. — These are granitoid rocks, the chief feldspar of which is acid plagioclase, and they are rich in hornblende. When biotite largely replaces the hornblende, the rock is called *mica-diorite.*

Again, augite may replace part of the other dark minerals, forming an *augite diorite*, which is a passage-rock to gabbro. Typically, the feldspar is in excess of the dark minerals, but in other cases these may lead in the mineral constituents. A rock of diorite composition may also arise by metamorphism of gabbros with the change of the augite to hornblende. Porphyritic diorites, occurring in dikes, have been called *camptonites*. Characteristic secondary minerals are: magnetite, titanite, and apatite. The name *diorite* was given to this rock because of the striking contrast between the light and dark minerals of which it is composed.

Andesites. — These are the fine-textured to felsitic members of the diorite series. The acid plagioclase feldspars are the most abundant minerals, but quartz is rare or absent. Biotite, hornblende, and augite are the dark minerals, the last two predominating over the biotite. The general colors of the rocks are grays or greens. Typical andesite is felsitic, sometimes cellular, and commonly porphyritic. The felsitic ground-mass consists of microscopic rods of feldspar, forming a felt-like aggregate. From trachyte and dacite it can generally be distinguished only by its darker color, owing to the greater abundance of the ferromagnesian silicates. According to the predominant dark mineral we have mica andesite, hornblende andesite, augite andesite, etc.

In the porphyritic varieties, the phenocrysts are mostly feldspar; when very abundant (up to half the mass) they form an *andesite-porphyry;* when in excess, a *diorite-porphyry*. These show an increasingly coarser ground-mass, and grade into diorites proper.

With increase in orthoclase, andesites pass into trachytes, and with increase in the dark and more basic ferromagnesian silicates and a decrease of feldspars, they pass into basalts; with addition of quartz they pass into dacites. The type localities for these rocks are in the Andes Mountains, and they are abundant and widespread in the Pacific Coast region of North America, especially in the old volcanic cones of Mt. Hood, Mt. Shasta, Mt. Rainier, and others.

The Glasses of the Diorite-Andesite Series. — Andesites fuse at temperatures around 2000° F. (1100° C.), which is about the same as for trachytes. Like these, therefore, they do not readily form glasses, and most of those referred to andesites are probably referable to the dacites. The glasses of this type which are recognized are: andesite-obsidian, andesite-perlite, and andesite-pumice.

They are distinguished from the more acidic glasses only by chemical analysis, or by their field relations to recognizable types of andesites or dacites. Andesite obsidian has been obtained from Clear Lake, Cal., andesite perlite from Eureka, Nev.

The Gabbro-(Pyroxenite, Peridotite)-Basalt Series

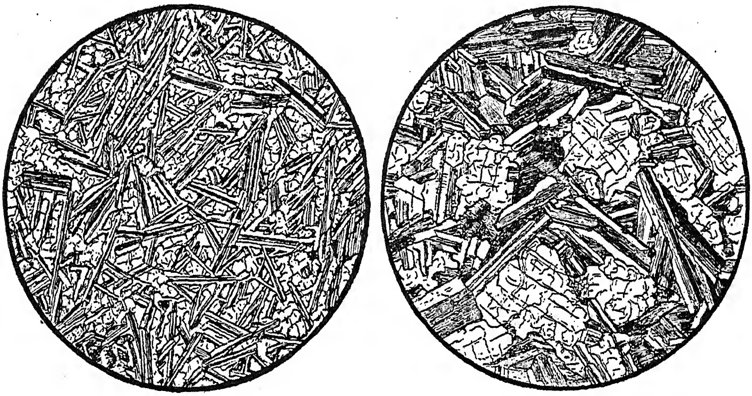
This includes all the basic igneous rocks, the coarser-grained members of which range through gabbro, olivine-gabbro, pyroxenite and peridotites, while the fine-grained ones form diabases and basalt. The surface flows are represented by scoriaceous, ropy, or other lavas, and more rarely by glasses (tachylite, Peele's hair, etc.).

Gabbro and Olivine Gabbro. — These are generally coarsely crystalline dark rocks, composed chiefly of basic plagioclase and monoclinic pyroxenes, the dark silicates typically predominating. There are, however, varieties which are almost wholly composed of coarse crystalline labradorite (Canada, Adirondacks) with little or no pyroxene. These are also called *anorthosites;* where the pyroxene is of the orthorhombic varieties (enstatite, bronzite, hypersthene), the rock is called *norite.* Gabbro may contain some hornblende and biotite. When olivine is present the rock becomes olivine-gabbro, olivine-norite, etc. In rare cases nephelite becomes an important mineral in some basic gabbros, forming the rock *theralite,* which occurs in the Crazy Mountains, Montana. Gabbros have a wide distribution.

Pyroxenites and Peridotites. — By the decrease of the plagioclase, the gabbros pass insensibly into pyroxenites and peridotites, which are usually found associated with the gabbros, but also occur independently. Pyroxenites generally contain little else than pyroxene, which may be orthorhombic (enstatite, bronzite, hypersthene) or monoclinic (diallage, augite), but these are not readily distinguishable by the unaided eye, though the orthorhombic pyroxenes show a bronze luster. Frequent accessory minerals are hornblende, magnetite, and pyrrhotite. When olivine is added the rock becomes a *peridotite,* and when olivine predominates it becomes a *dunite,* of which the nearly pure olivine rock of North Carolina is an example. Sometimes magnetite is so abundant as to make the rock almost an iron ore. Porphyritic peridotites have been called *picrites,* especially when occurring in dikes. Sometimes hornblende is abundant, and it may even form a rock by itself, which is then called *amphibolite.*

Pyroxenites and peridotites change with age and by metamorphism into serpentines.

Diabase. — This is a transitional rock between the gabbros and the basalts, being fine-grained but holocrystalline and differing in detail of texture from the gabbro. It consists of basic plagioclase, augite, and often olivine, the first occurring as elongated rectangular rods arranged in an interlacing manner, while the other



a *b*

Fig. 47. — *a*, Basalt, showing typical diabasic structure of lath-shaped crystals of plagioclase, Burney Falls, Shasta Co., Cal. *b*, Bronzite diabase, York, Pa., showing lath-shaped plagioclase crystals. Both sections are seen under crossed nicols enlarged 24 times (after Rosenbusch).

minerals are packed in between them in irregular masses. This is brought about by the fact that the plagioclase crystallized out first, contrary to the usual order of crystallization, and that the ferromagnesian minerals had to adapt themselves to the remaining spaces. This *diabasic texture* (Fig. 47) is sometimes modified into an *ophitic* one, where the rods of plagioclase are included in large, coarsely crystalline masses of pyroxene. Diabase is common as an intrusive rock, both as dikes and sills.

Basalt. — These are the basic fine-grained or dense igneous rocks which form the surface flows of the gabbros, pyroxenites, and peridotites. Typically the texture is dense or felsitic, often cellular, and the rock may be characterized by almond-shaped steam holes which are subsequently filled with secondary calcite, giving the rock an *amygdaloidal* structure (Fig. 48). Sometimes these cavities are filled with copper, as in the Lake Superior region. Por-

phyritic basalts show phenocrysts of augite and more commonly olivine. Such porphyritic olivine basalts are also called melaphyres. The felsitic ground mass is composed of microscopic augite, plagioclase and magnetite crystals. Sometimes a little glass is present. With abundant development of phenocrysts, of augite and olivine, the rock becomes a *basalt porphyry* and with excessive development of phenocrysts a *gabbro porphyry* is produced.


FIG. 48. — Amygdaloid.

In rare basalts nephelite or leucite may replace the feldspar, giving a variety of types, distinguishable only under the microscope.

Augitites and Limburgites. — These are rare basaltic rocks, with little or no feldspar, which correspond to the pyroxenites and peridotites, respectively.

The Basic Glasses. — These represent surface formations of the basaltic flows, but are on the whole not common. Some of the porous or vesicular scoria is glassy, but for the most part it has a dense stony or felsitic texture. Typical basic glass, corresponding to obsidian, is known by the name of *tachylite*, while a fibrous variety found in the crater of Kilauea is called Pele's hair.

Special Field Names

Several names are commonly applied to the basic igneous rocks when the exact character cannot be determined in the field. One of these is *dolerite*, used for rocks which may be diorites or gabbros, but in which the dark mineral is undeterminable. Another is *trap*, in common use for dark, dense basalts or diabases. It is derived from the Swedish trappar, a stairway, because the sheets of this rock sometimes form successive steps in the landscape. Old trap or basaltic rocks which have, by alteration, developed sufficient of the mineral chlorite to give them a greenish cast, are called *greenstones*.

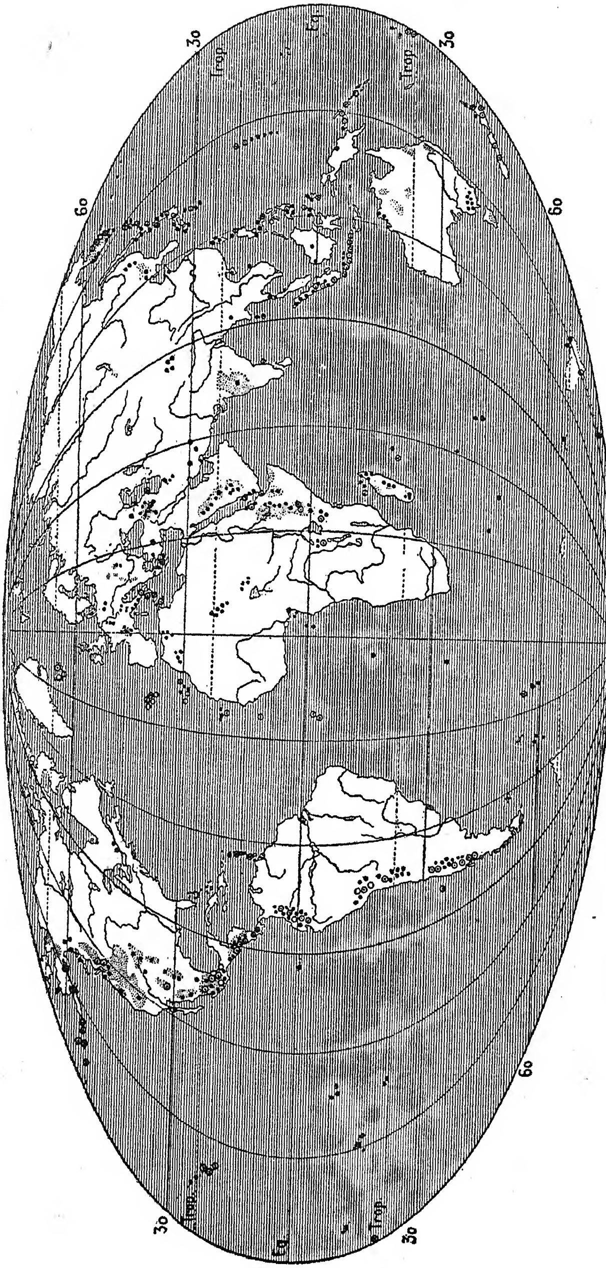


FIG. 49.—Map showing distribution of volcanoes. (After Martonne.)
Circles with dots: Volcanoes active in 19th Century.
Plain circles: Volcanoes active before the 19th Century.
Black dots: Extinct volcanoes.
Stippled areas: Volcanic regions and lava fields.

CHAPTER VII

MODERN VOLCANIC PHENOMENA

EXCEPT in the case of comparatively young volcanic eruptions, the structures and relationships of igneous masses can be studied only in regions where these masses have been uncovered by erosion of the rocks which formerly covered them, and their origin can be determined only from the available facts. We shall first consider those masses the formation of which are open to observation or which have been formed so recently that there can be no doubt as to their origin.

DISTRIBUTION, CLASSIFICATION, AND DEVELOPMENT OF VOLCANOES

Volcanoes are found in many parts of the world at the present time, but their most extensive distribution is around the borders of the Pacific, where they form a "chain of fire" which surrounds that ocean. The map on the opposite page shows this and their occurrence elsewhere. Along the western border of the Pacific more than 150 active volcanoes are distributed through a length of 16,000 kilometers, while about 100 border the eastern margin of that ocean from the Aleutian Islands to Tierra del Fuego. Typical and perfect examples of the former are Fujiyama in Japan (Fig. 50) and Mayon in the Philippines (Frontispiece), while Bogosloff and Popocatepetl may serve as examples of the latter. Within the Pacific and arising from its floor are other active volcanoes, such as those of the Hawaiian Islands, near its very center, and those of the southwest coral reef regions.

On the Atlantic borders, active volcanoes are not common, being chiefly confined to the Antillean region in the west, the Icelandic in the north, and the Azores, Canaries, and Cape Verde Islands in the east. These are in reality local or isolated groups of volcanoes, except those of Iceland, which are the last manifestations of volcanic activity in a vast volcanic field which extends from Greenland on the west to Siberia on the east, and which began far back in

FIG. 50. — Fujiyama, a perfect volcanic cone in Japan.

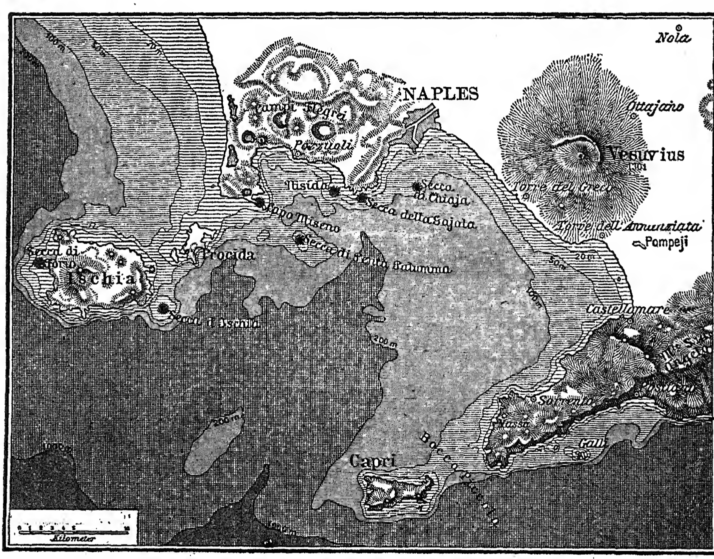


FIG. 51. — Map of the Naples volcanic region, with the three principal volcanic centers, — Vesuvius, the Phlegræan volcanic field west of Naples (Pampi Flegrei), and the Island of Ischia; together with the submarine volcanoes. (After J. Walther, from Ratzel.)

the geological history of the region. In the Mediterranean are three important fields of volcanic activity known since ancient times: that around Naples, that of Sicily and its islands, and that of the Grecian archipelago. The Naples volcanic field (Fig. 51) comprises Vesuvius with Monte Somma on the east of Naples, the Phlegræan volcanic field with a number of vents including

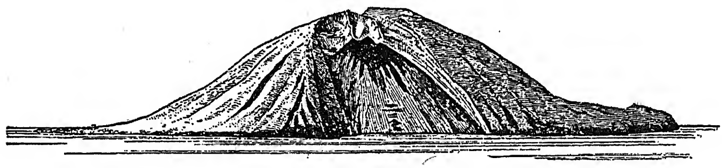


FIG. 52. — View of Stromboli from the northwest. (After A. Bergeat, from Kayser's *Lehrbuch.*)

Monte Nuovo, the Solfatara, the Pozzuoli district, etc., on the west, and the volcanic island of Ischia on the southwest, besides many smaller islands, including Capri on the south. The Sicilian region includes Mount Etna in the northeastern part of that island, and the volcanoes of the Lipari or Æolian group of islands north of Sicily, among which are Vulcano and Stromboli (Fig. 52), the latter called the "Lighthouse of the Mediterranean," because of the

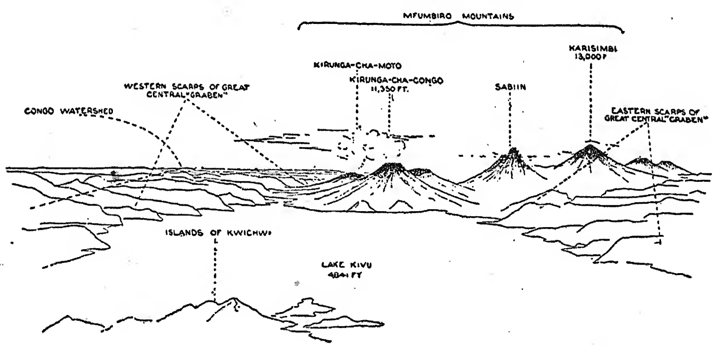


FIG. 53. — Volcanoes of the great Rift Valley of East Africa. (After Moore.)

flashes of its explosions, given off at intervals of from 1 to 20 minutes. In the Grecian archipelago the island of Santorin has been a scene of volcanic activity for more than 2000 years. Volcanoes are also active around the Indian Ocean, especially on the islands which form its eastern margin. Active volcanoes exist in the great "Rift Valley" of East Africa, in which lie many of the large lakes of that region (Fig. 53), and recently extinct volcanoes occur along

the northern margin of the Indian Ocean in Arabia, while more ancient volcanic activities are recorded in India.

Active, Dormant, and Extinct Volcanoes

Volcanoes may be classed as *active* when eruptions are occurring at intervals; as *dormant*, when they have been quiescent for centuries, though the possibility of a new eruption exists; and as *extinct*, when volcanic activity has entirely ceased and the volcano is undergoing destruction by atmospheric agencies. There is of course every gradation between these; some that would be classed as dormant may never be revived, while others, after a long sleep, burst forth again, as in the case of Vesuvius at the beginning of the Christian Era. It should be clearly understood that volcanism is not a phenomenon restricted to the present, but that volcanic activities, often on a much grander scale than those of to-day, have been going on during all the periods of the earth's history. Many of the older volcanoes and their products, after suffering more or less destruction by erosion, were buried under more recent deposits, and have been reëxposed only in part as the result of the latest phases of erosion.

Formation of New Volcanoes in the Historic Period

Most of the modern volcanoes came into existence before the time of recorded history, but a few have been formed during the historic period, and their growth and development has been witnessed by man. The most noted of these are: *Monte Nuovo*, in the Bay of Baiæ near Naples (1538); *Jorullo*, Mexico (1759); *Pochutla*, Mexico (1870); *Camiguin*, Philippine Islands (1871); a new cone of the *Ajusco group*, Mexico (1881); the *New Mountain* of Japan (1910); and the submarine cones of *Sabrina* and *Graham Islands* (1811 and 1831). A few of these may be considered in some detail.

Monte Nuovo. — This volcano (Fig. 54) arose in the Phlegræan fields west of Naples on Sunday, September 29, 1538, beginning about one o'clock in the morning. It appeared mainly on the site of the ancient Lake Lucrinus, which itself was regarded as the crater of an older but extinct preëxisting volcano, filled with water. Incandescent gases burst open the earth, and within a week a cone made up of ejected ashes, cinders, and large stones, but no lava, was built up to a height of 440 feet above the level of the sea. The

depth of the crater is 421 feet, reaching within 19 feet of the sea-level, and its basal circumference about 8000 feet. The eruption was preceded on the day and night before by about twenty earthquake shocks in Pozzuoli and the neighborhood, and after the eruption it was found that the sea had receded for some distance, owing

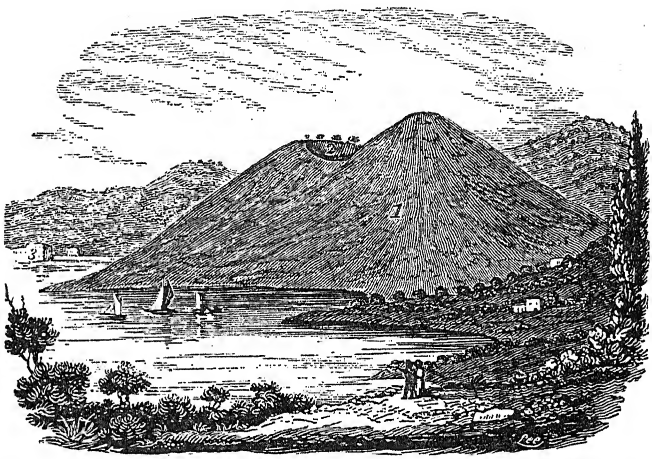


FIG. 54. — Monte Nuovo, formed in the Bay of Baiæ, Sept. 29, 1538. (After Lyell.) 1. Cone of Monte Nuovo. 2. Rim of crater of same. 3. Thermal spring called Bath of Nero, or *Stufe di Tritoli.*

to the elevation of the region, and the strand was covered with quantities of dead fish, as well as dead birds.

The cone of Monte Nuovo is very regular, and is composed of layers of pumaceous fragments and ashes, and of trachytic blocks, the whole partly consolidated and dipping away from the crater at angles of 26 to 30 degrees. Fragments of marine shells and Roman bricks were also included in the beds as a result of the disturbance of the region by the explosions.

Jorullo. — This cone arose on the night of September 28, 1759, at a point 35 miles distant from any then existing volcano, and 120 miles from the sea. It appeared on a level plain 2000 to 3000 feet above the sea in the state of Michoacan, Mexico. A northeasterly fissure opened in the midst of the sugar and indigo fields of this plain, and ashes and rocks were thrown to a great height, and on falling these built up six conical hills on the line of the chasm, the smallest 300 feet high, while Jorullo itself was built up to 1600 feet above the plain, or 4265 feet above sea-level. Great streams

of basaltic lava were poured forth from Jorullo, these including fragments of granitic rock. The ejection did not cease until February, 1760. Twenty years later the lava was still hot enough, a few inches below the surface, to light a cigar. This eruption, too, was preceded by earthquakes and subterranean rumblings, which began in the June preceding. There has been no eruption in this region since.

Camiguin. — This volcano also started from a fissure in a level plain on one of the small islands north of Luzon in the Philippines. Beginning in 1871, it continued to be active for four years, by which time it had reached a height of about 1800 feet.

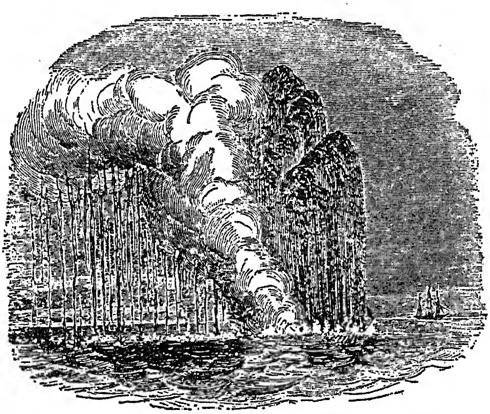


FIG. 55. — The volcanic eruption which formed Sabrina Island in the Azores, June 13, 1811. (After De La Beche.)

Sabrina Island. — This submarine volcanic cone appeared above the waters of the Atlantic in the Azores group, off the coast of St. Michaels, on June 13, 1811, and rose to a height of about 300 feet above the sea, gaining a circumference of about a mile. Being, however, largely made of unconsolidated material, it has since been washed away again. As observed from the nearest cliff on St. Michaels, the explosions resembled a mixed discharge of cannon and musketry and were accompanied by a great abundance of lightning. The appearance of the eruption above water is shown in the accompanying figure from a sketch made at that time (Fig. 55).

Graham Island (Isle Julia). — This island, which existed for only about three months, rose as a submarine cinder cone in 1831 in the Mediterranean between the southwest coast of Sicily and that projecting part of the African coast where ancient Carthage stood. A few years before the appearance of the island, soundings at this locality showed a depth of water of 100 fathoms. Premonitory shocks were felt on June 28 over the spot and on the adjoining

coast of Sicily. About July 10, a column of water 60 feet high and 800 yards in circumference was seen rising from the sea, followed soon after by dense clouds of steam which rose 1800 feet. Eight days later the same observer noted at this spot a small island 12 feet high and with a crater at its center, from which volcanic matter and immense clouds of vapor were ejected, while the sea round about was covered with floating cinders and dead fish. By the end of July the island had become from 50 to 90 feet in height and three fourths of a mile in circumference, while on August 4 it was reported above 200 feet high and three miles in circumference. After this it began to diminish in size, owing to the erosion by the sea, decreasing to two miles in circumference by August 25, and to three fifths of a mile and a maximum height of 107 feet by September 3, when the crater was about 780 feet in circumference. On September 29 the island was reduced to a circumference of only about 700 yards, and toward the close of October it had disappeared except for a small point of sand and scoriæ. By the commencement of 1832 there was only a shoal, with a mass of igneous rock which apparently filled the center of the vent. The appearance and supposed structure of this island and of the cone, which rose thus about 800 feet above the sea floor, are shown in the above figures reproduced from Lyell (Figs. 56, 57). The lava core or

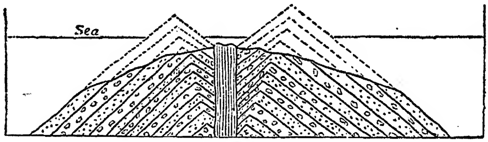


FIG. 56. — Supposed section of Graham Island. (After C. McLaren, Geology of Fife and the Lothians, pl. 41, Edin., 1839; from Lyell's *Principles.*)

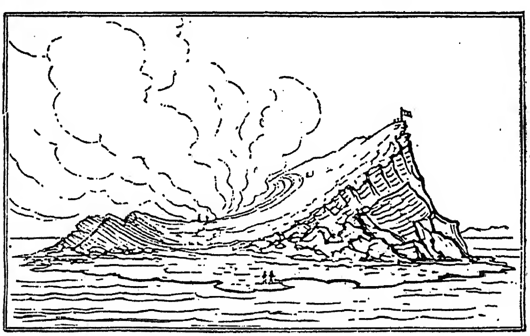


FIG. 57. — Graham Island, as it appeared on Sept. 29, 1831. The apparent bedding planes sloping towards the center of the volcano are not such in reality. (From Lyell's *Principles.*)

neck, which probably never appeared above sea-level, now forms the highest part of the submerged remnant of the volcano. The fragmental material included, besides volcanic ash and cinders, blocks of limestone, dolomite, and sandstone.

Several other submarine eruptions of this type have been recorded from various sections of the Atlantic and from the Mediterranean.

Characteristic Forms and Activities of Typical Modern Volcanoes

Of the many modern volcanoes, a number which have been observed for long periods of time may be described somewhat in detail so that the student will get a grasp of the essentials of the structure and activities of volcanoes. We shall begin with a type in which liquid lava is the chief product of eruption, then consider types in which both lava and fragmental material are produced, and enter into the building of the cone, and finally consider some examples which are purely explosive, with the production of only fragmental material. The nature and composition of the fragmental material will be considered more at length in a subsequent chapter.

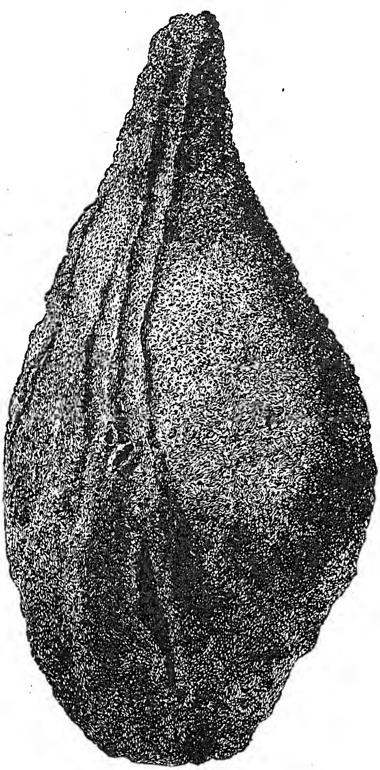


Fig. 58. — Volcanic bomb. Vesuvius, eruption of 1872. (After Ratzel, *Die Erde.*)

Before proceeding, the student should clearly understand that the hill or mountain which constitutes the volcano is built up around an opening or *vent* from the material ejected from this vent, and that it does not represent an upris-

ing or an upheaval of a part of the earth's surface, as was at one time supposed to be the case. Three kinds of material are ejected from volcanic vents; of these, two or all may be present. The first type comprises *gases* and *water vapors* mingled with fumes of other substances; this is always present. The second is liquid magma or *lava*, and the third consists of the shattered lava and shattered rocks resulting from the explosive activities, comprising masses of all sizes, from large lava balls or bombs (Fig. 58), more or less spherical or elliptical from their rotary motion through the air, to fine lava particles or *lapilli*, and fragments or blocks of older igneous or other rocks, and dust produced by the shattering of these. In general we speak of such material as volcanic ashes and cinders. The eruptive activities range from the quiet upwelling or bubbling-up of liquid lava to the most violent explosion due to the sudden expansion of the gases and vapors.

Kilauea (and Mauna Loa) of the Hawaiian Islands

The entire group of the Hawaiian Islands (Fig. 59) in the mid-Pacific is a series of volcanic cones built up from the sea-bottom in former times. Most of these volcanoes are now extinct, and many

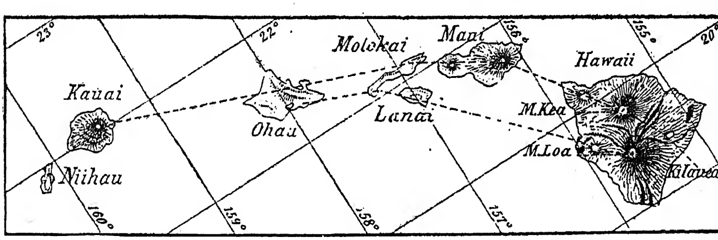


FIG. 59.—Map of the Hawaiian Islands, showing the principal craters. (After Dana.)

of them are undergoing erosion; but a large, active crater, that of Kilauea (4000 feet above sea-level), exists on the east side of the volcanic mountain of Mauna Loa (13,675 ft. high) and about twenty miles from its summit, which is also marked by an active crater. The crater pit of Kilauea (Fig. 60) is rudely oval in form, with a circumference of about nine miles, and its floor is formed by a rough stony crust of solidified lava — resting upon a vast column of molten rock which arises from an unknown depth in the crust of the earth. In places, this floor is broken by lakes of liquid lava, red to white

hot, and set into boiling activity by the ebullition of gases (Figs. 61, 62). From cracks in the floor and on its margin jets of lava are

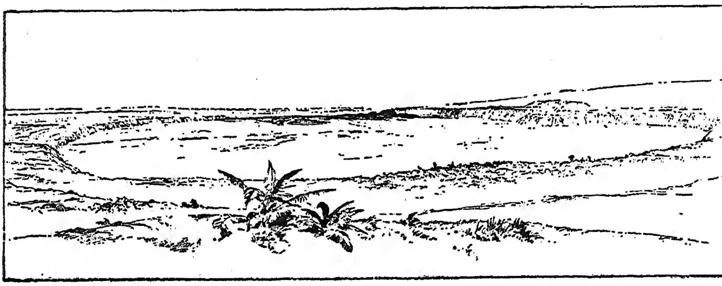


FIG. 60. — View of outline of the crater of Kilauea from Volcano House. (After Dutton.)

frequently projected to great heights, and some of this material, blown like spray by the wind, is drawn out into slender, hair-like fibers. This has become known as Pele's hair, so named after the goddess of the mountains.

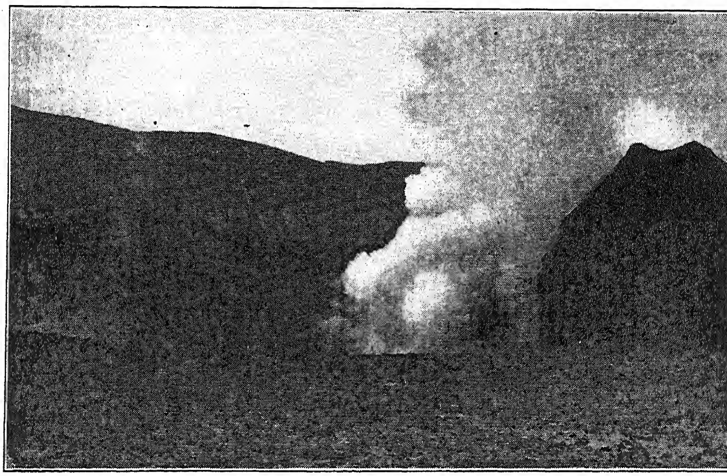


FIG. 61. — The Lava Lake at one side of the crater of Kilauea.

The margin of the crater is formed by a precipitous cliff which varies in height from time to time. This is due to the fact that the lava column which supports the floor rises as the pressure increases below, until a point is reached where the wall may be ruptured, and the liquid lava flows out, whereupon the column dimin-

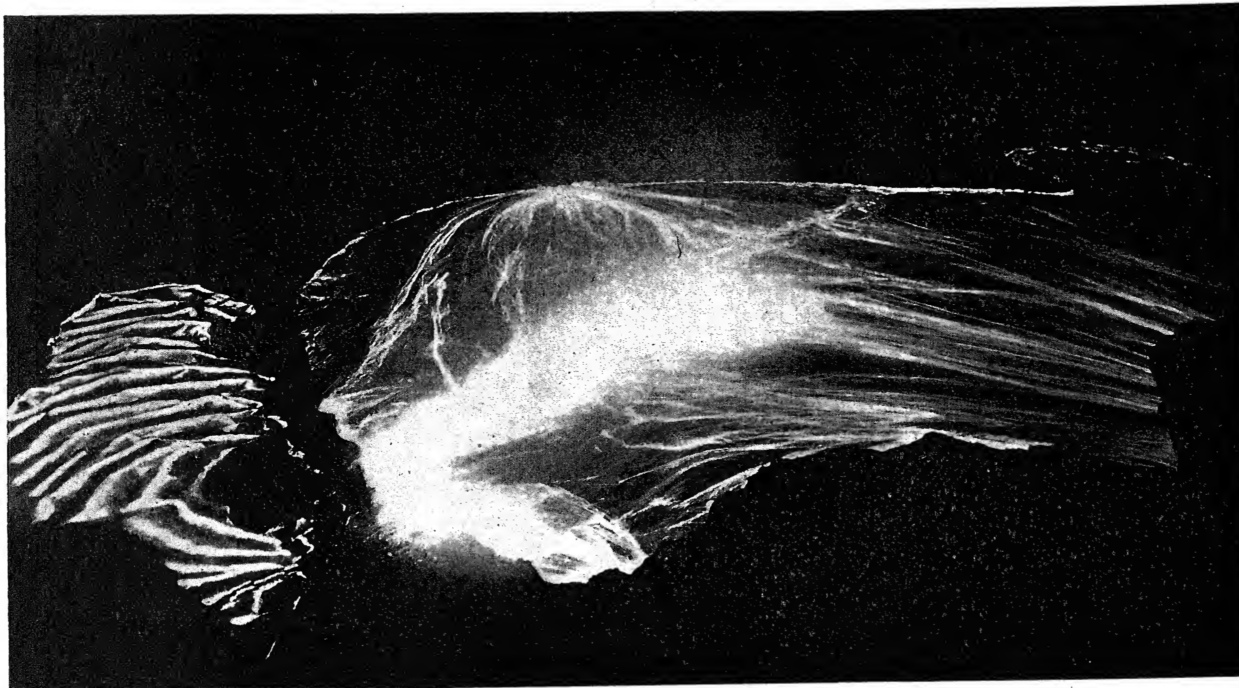


FIG. 62.—The Lava Lake of Kilauea, in January, 1912. (Courtesy of the American Geographical Society, Broadway at 156th St. From the *Geographical Review*.)

ishes, carrying the floor downward, until it may be 700 feet below the edge of the crater rim. The rate of rising may be as much as 100 feet in a year, but in modern times the lava has not overflowed the rim, but issues from lateral fissures due to cracking or fusion, the floor approaching only to within 300 feet of the edge of the

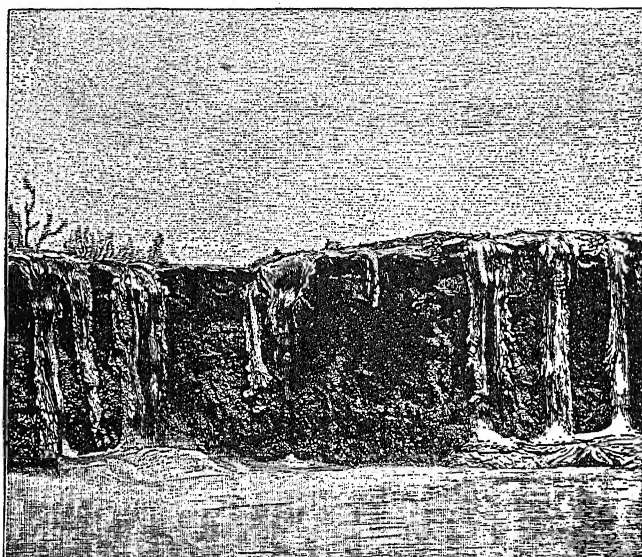


FIG. 63.—A lava stream falling in cascades over a cliff into the sea, Hawaiian Islands.

crater. During the eruption of 1840 the lava first appeared on the side of the mountain five miles from the main crater, after which it issued at successively lower levels.

Similar conditions exist in the crater of Mauna Loa proper, but here the top of the lava column is nearly 10,000 feet above that of Kilauea.

The lava of these volcanoes is very liquid, being of an extremely basic character and forming basaltic rocks on cooling. Because of its liquidity, it will continue to flow for a long time; some of the lava flows of Hawaii are thirty miles in length. When it reaches a cliff, the lava cascades over it like a waterfall (Fig. 63). The surface of such lava streams often shows local wave-like advances, which produce the appearance of a series of crushed pillows piled one against the other. This type of surface form is known in Hawaii

as Pahoehoe (pron. *pa-hoi-hoi*) (Fig. 64), and it is seen in older lavas of this type in many regions of the world. A ropy surface, having the appearance of coils of heavy rope, is also commonly produced. Compare also with Fig. 66.

As the lava stream moves along, it sweeps away forests in its course, and carries away masses of rock and soil covered with vege-

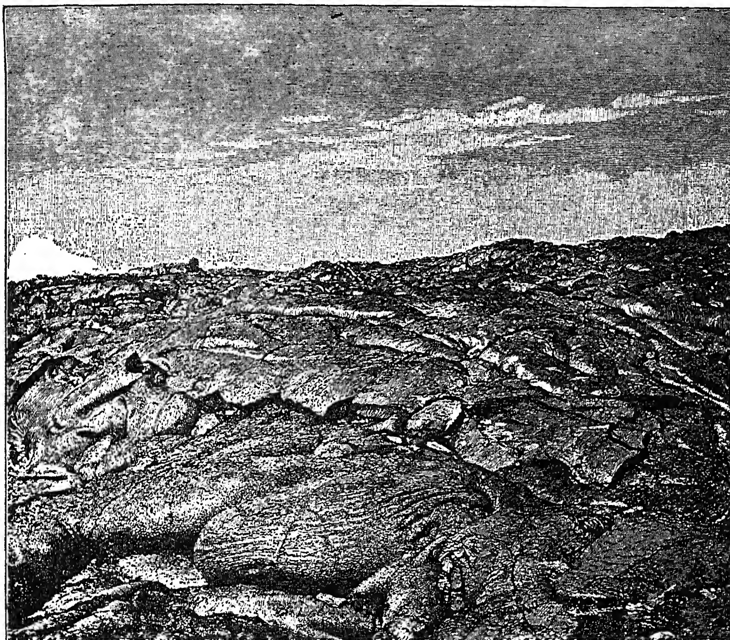


FIG. 64. — Sluggish lava flow forming pillow lava or "pahoehoe" on Mauna Loa.

tation (Fig. 65). Sometimes a stream will part around a mass of such rock and, reuniting, enclose it as an island. On reaching the sea, the lava plunges into it with loud detonations and becomes shivered into millions of particles of glass, which may be thrown in clouds into the air. The light from such an eruption has been visible for over a hundred miles at sea, and at a distance of forty miles fine print could be read at midnight (Dana).

When the crust of the lava stream has cooled, the interior mass, still in a molten condition, will flow on, leaving a tunnel behind. Such tunnels are common in Hawaii, and their roofs are frequently

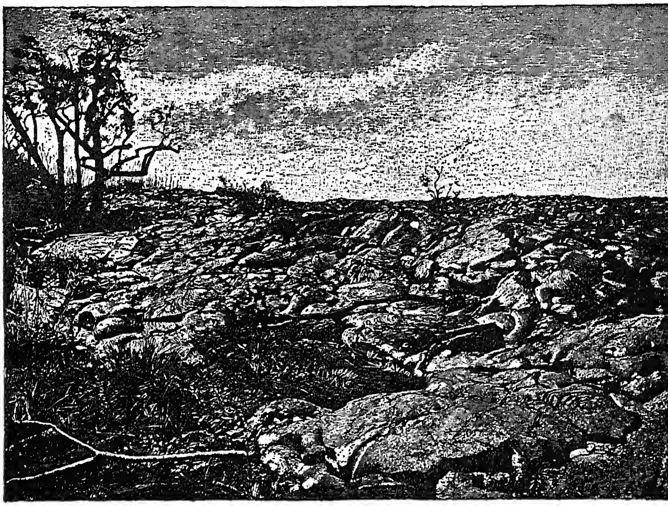


FIG. 65. — End of the lava flow of 1881 on Mauna Loa. Note the trees which were killed but not consumed, and those which escaped.

incrusted with lava pendants or stalactites up to 20 or 30 inches in length, while on the floor corresponding drip mounds or stalagmites of lava are found. Small "spatter cones" may also arise on its surface (Fig. 66).

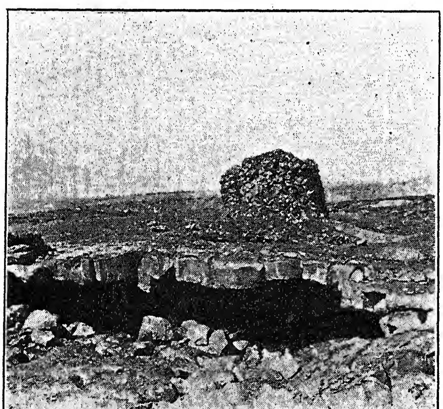


FIG. 66. — Lava tunnel formed by the cooling of the outer surface of the flow, after which the lava within flows out, leaving the tunnel. On the surface of the flow a spatter cone was built up. Hawaiian Islands.

The form of these basic lava volcanoes is very characteristic, being a very flat cone of vast dimensions. As they arise from the sea-bottom, only a small part is visible, the total height of Mauna Loa being more than 30,000 feet, although considerably less than half of this height is seen. The summit is nearly flat for several square miles, and the slopes of the sides do not average more than seven degrees.

Craterless Volcanoes of Viscous Lava

When the lava is very viscous, such as is characteristic of very silicious (acidic) lavas, it may happen that the lava mass rises as a dome-like swelling from the surface, producing a mound or hill of lava which is not characterized by a summit crater. The volcano of Chimborazo in Ecuador (20,498 feet above the sea) appears to

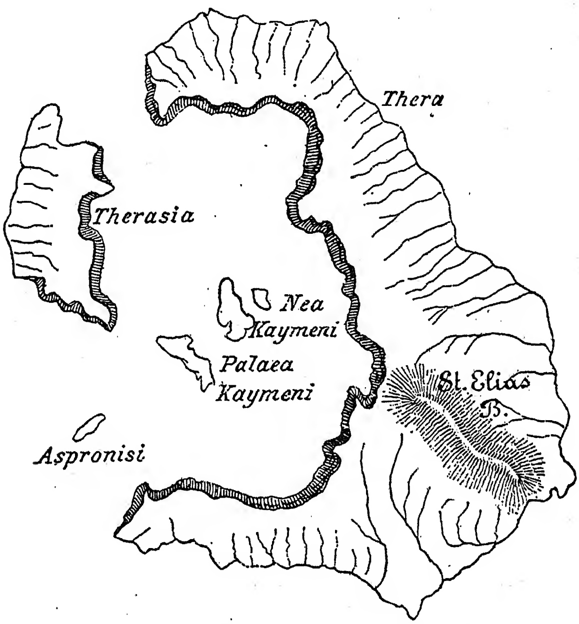


FIG. 67. — Map of the ruin of the cone of Santorin, in the Greek Archipelago. (From Kayser's *Lehrbuch.*)

be of this type, and an eruption of this character occurred in 1866 which formed the Isle of Asphroessa at Santorin in the Grecian Archipelago (Figs. 67, 68). A gradual rising of the bottom of the bay occurred, until the island appeared, which apparently was due to slow upward and outward pressure by steam, which was escaping at every pore through the scoriaceous lava surface. The red-hot lava could be seen through the fissures, and the whole mass was undulating and swaying from side to side, sometimes appearing to swell to nearly double its size, and to throw out ridges like mountain spurs. At last a broad chasm appeared across the top of the cone, accompanied by a tremendous roar of steam, while rocks and

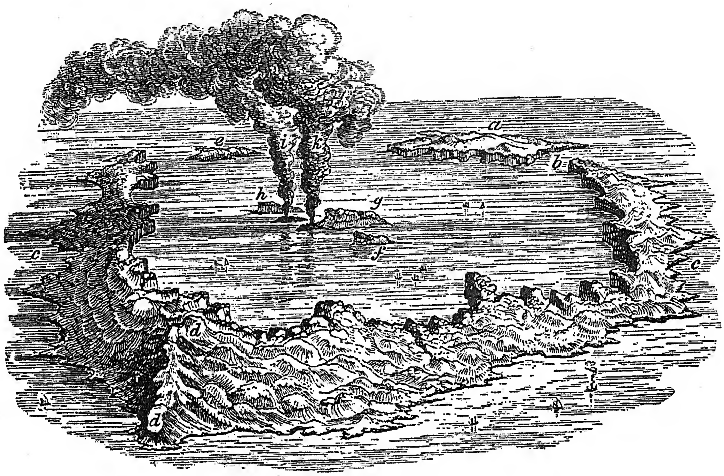
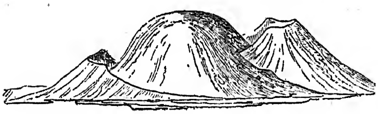


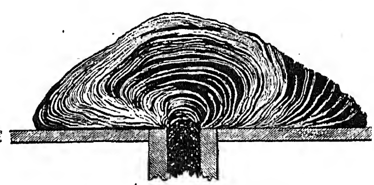
Fig. 68.—Bird's eye view of the Gulf of Santorin, during the volcanic eruption of February, 1866, looking west. (From Lyell's *Principles.*) *a.* Therasia. *b.* The northern entrance, 1,068 feet deep. *c.* Thera. *d.* Mt. St. Elias, rising 1,887 feet above the sea, composed of granular limestone and clay-slate; the only non-volcanic rocks in Santorin. *e.* Aspronisi. *f.* Little Kaimeni (Kaymeni or Kæmenæ). *g.* New Kaimeni (Nea Kaymeni or Kæmenæ). *h.* Old Kaimeni (Palæa Kaymeni or Kæmenæ). *i.* Asphroessa. *k.* George.

ashes mixed with steam were thrown to heights of 50 to 100 feet, masses of this material, 30 cubic feet in bulk, falling at distances of 600 yards from the new crater. Then the activity subsided, the cone was lowered, the crater closed in, and after a few minutes of quiet the process recommenced.



a

Fig. 69 *a.*—Grand Puy of Sarcoui, composed of trachyte and rising between two breached scoria cones; a typical example of a pustular cone or volcanic blister formed of highly viscous lava. Auvergne, France.



b

Fig. 69 *b.*—Experimental illustration of the mode of formation of volcanic blister cones composed of viscid lavas.

An example of such a *blister cone* or *volcanic dome*, now extinct, is found in the Grand Puy of Sarcoui (Fig. 69 *a*) in the old volcanic district of Central France. This mountain is a mass of trachyte

lava having the appearance of an inverted cup, without a crater, and was apparently formed from a mass of viscous lava which was forced upward to form a blister upon the surface of the earth. Blisters of this kind have been reproduced experimentally, as shown in the preceding figure (Fig. 69 *b*).

Vesuvius

A very different type of volcano is represented by Vesuvius, probably the best and longest known of active volcanoes. The

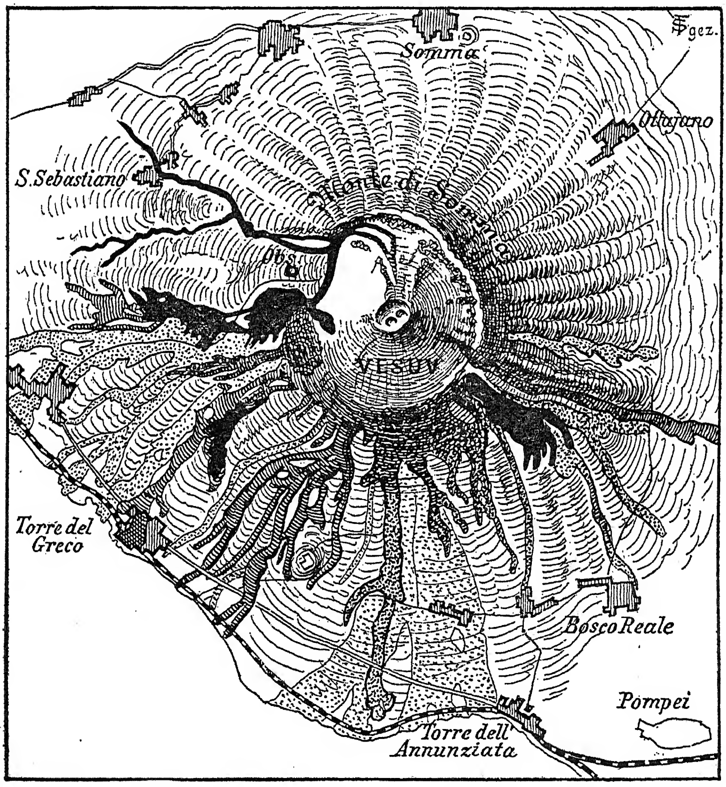


FIG. 70. — Map of Vesuvius with its lava streams up to 1872. The darker are the later, and lighter the earlier flows. Scale about 1 : 250,000. After Le Herr and others. (From Kayser's *Lehrbuch.*)

present cone, which lies east of Naples, is surrounded on three sides by the rim of the ancient cone, now called Monte Somma (Figs. 70, 71), which was perfect up to the first century of the Christian

Era. That volcano had been dormant for so long that its slopes were clothed with vineyards and gardens and dotted over with villas, while at the foot of the mountain lay the populous cities of Herculaneum and Pompeii. Even the interior slopes of the crater, of which only a part remains in Monte Somma, were covered with wild vines, so Plutarch tells us, while the floor of the crater was a sterile plain. On this plain, from which there was only a single outlet, a break in the wall of the crater, the gladiators of Spartacus encamped in 72 B.C., while the prætor Clodius guarded the outlet and attacked Spartacus by lowering his soldiers into the crater over the precipitous walls.

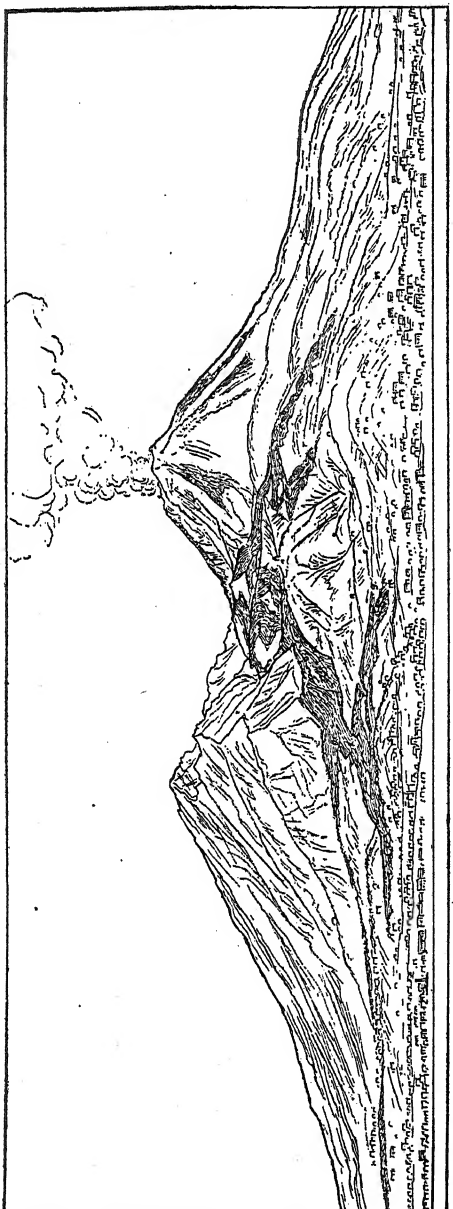


FIG. 71. — Vesuvius as seen from Naples with the lava streams of 1872 in dark. After A. Heim. Monte Somma on the left. (From Kayser's *Lehrbuch.*)

In the year 63 A.D. the first evidence of the reawakening of the volcano made

itself felt in an earthquake which damaged the cities in the vicinity. From that time to 79 A.D. slight shocks were frequent, and in August of that year they became more numerous and violent, finally terminating in the first great historic eruption. As described by the younger Pliny, a dense column of vapor first arose vertically from the crater, spreading out laterally so that the

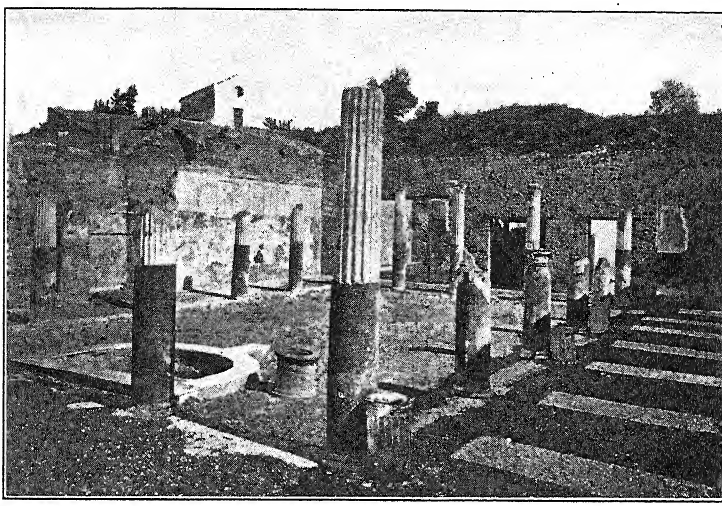


FIG. 72.—Ruins of Pompeii.

upper part resembled the head, and the lower the trunk, of a pine tree. Flashes of light, vivid as lightning, at intervals pierced this cloud, and ashes began to fall even upon the ships at distant Misenum, shoaling the sea in places and burying Herculaneum and Pompeii (Fig. 72). The violent explosions shattered the crater rim, of which only a part remains in Monte Somma, and the later cone of Vesuvius proper was built upon the floor of the old crater, surrounded on three sides by its rim. No lava appears to have been ejected at this time, the material being all of the pyroclastic or fragmental type, such as lapilli, sand, and fragments of older lava.

The first lava stream recorded from Vesuvius flowed in the eruption of 1036; which was the seventh since the reawakening of the volcano. Another eruption occurred in 1049, and still another in 1138 or 1139; after this the volcano rested for 168 years, though two minor vents opened at distant points, one at Solfatara, near Pozzuoli (Bay of Baiæ), in 1198, and the other on the island of

Ischia in 1302. Then in 1306 a minor eruption of Vesuvius took place, after which this volcano again became dormant for 325 years or until 1631, with one slight eruption in 1500. During this interval the Sicilian volcano Etna was, however, in constant eruption, while within the Phlegræan volcanic field west of Naples arose the new volcano Monte Nuovo in 1538 (*ante*, p. 112). Between 1139 and 1631, or for 492 years, there had been no violent eruption, and the

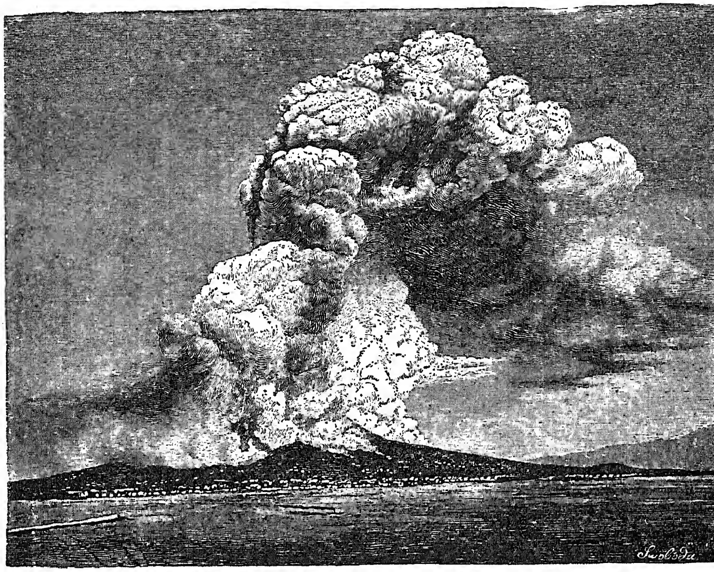


FIG. 73. — Eruption of Vesuvius in 1872. (After photograph from Ratzel.)

crater, which was five miles in circumference and about a thousand paces deep, had its sides covered with brushwood forests frequented by the wild boar, while cattle grazed on its floor. Three small pools of water remained upon the floor of the crater, one being hot and bitter, another more salty than the sea, and the third hot but tasteless. Suddenly, in 1631, the floor and sides of the crater were blown to fragments which the wind scattered, and in December of that year seven streams of lava poured forth from the crater, overwhelming several villages on the flanks and at the foot of the mountain, one of which, Resina, had been partly built over the ancient site of Herculaneum. Great floods of mud, from the condensed vapor and the ashes, also poured down the sides of the volcano and did much damage.

After a brief rest, the eruptions were renewed in 1666, since which time they have occurred almost constantly, with only short intermittent periods of quiescence (Fig. 73). The last great eruption occurred in 1906. This began with premonitory explosions in 1904, while during the whole of 1905 a narrow stream of lava flowed from a fissure in the cone (Fig. 74). On April 4, 1906, began the last great eruption, which was inaugurated by the appearance of a cloud of dust, carried aloft by the gases, and assuming the shape of

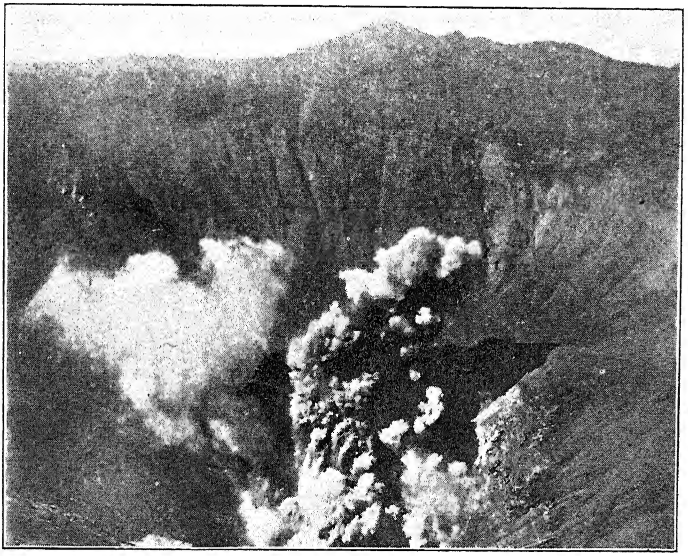


FIG. 74. — Looking into the crater of Vesuvius; hot lava sending up clouds of steam.

a cauliflower. At the same time several lava streams broke out at successively lower levels in the side of the cone. Three days later (April 7) occurred a violent explosion, and a dust cloud arose vertically into the air for a height of four miles, this dust falling in such quantities upon the roofs of the houses in the near-by towns as to cause their collapse. Larger streams of lava also issued from various openings, one of them reaching the town of Boscotrecase and destroying it. The main lava stream descended the steeper slopes at a rate of somewhat less then two miles an hour, but flowed at a much lower rate on the gentler slopes. The lava had a temperature of more than 2000° F., but owing to the rapid cooling

on the surface it did not burn up the trees with which it came in contact, but charred them, and sometimes broke them off by its weight and carried them along on its surface.

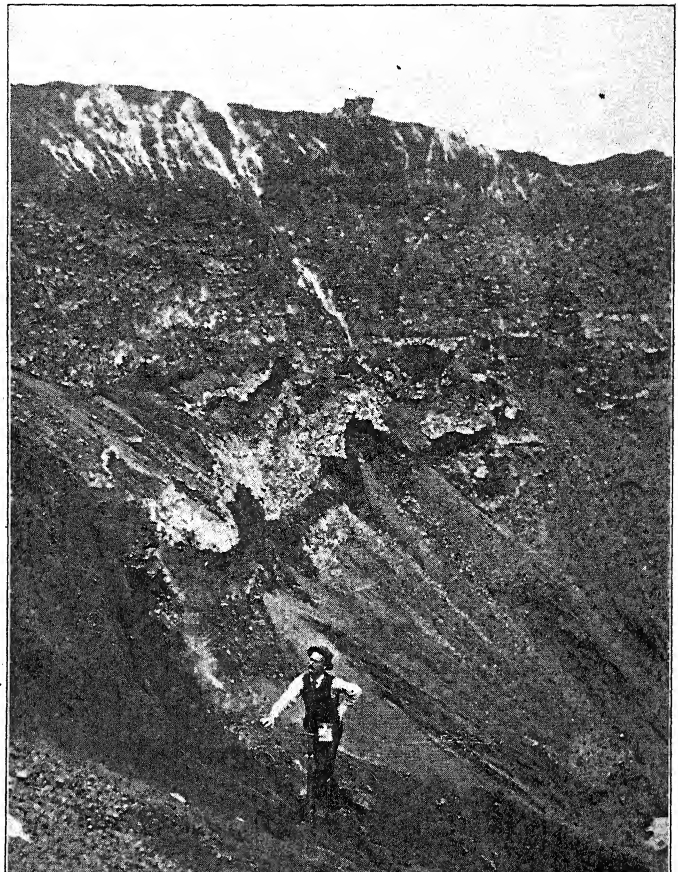


FIG. 75. — Inside the crater of Vesuvius. Note the stratified appearance of the wall of ashes and cinders, and the slopes of loose material.

Both the old cone of Monte Somma, and the later cone of Vesuvius, which has a height of about 4000 feet, are built up of layers of cinders, ashes, and lava (Fig. 75). These have a steep inclination, dipping away from the rim of the craters in all directions at angles of 26° to 40° or more. These layers are cut vertically by numerous fissures, which are filled with hardened lavas, forming dikes which

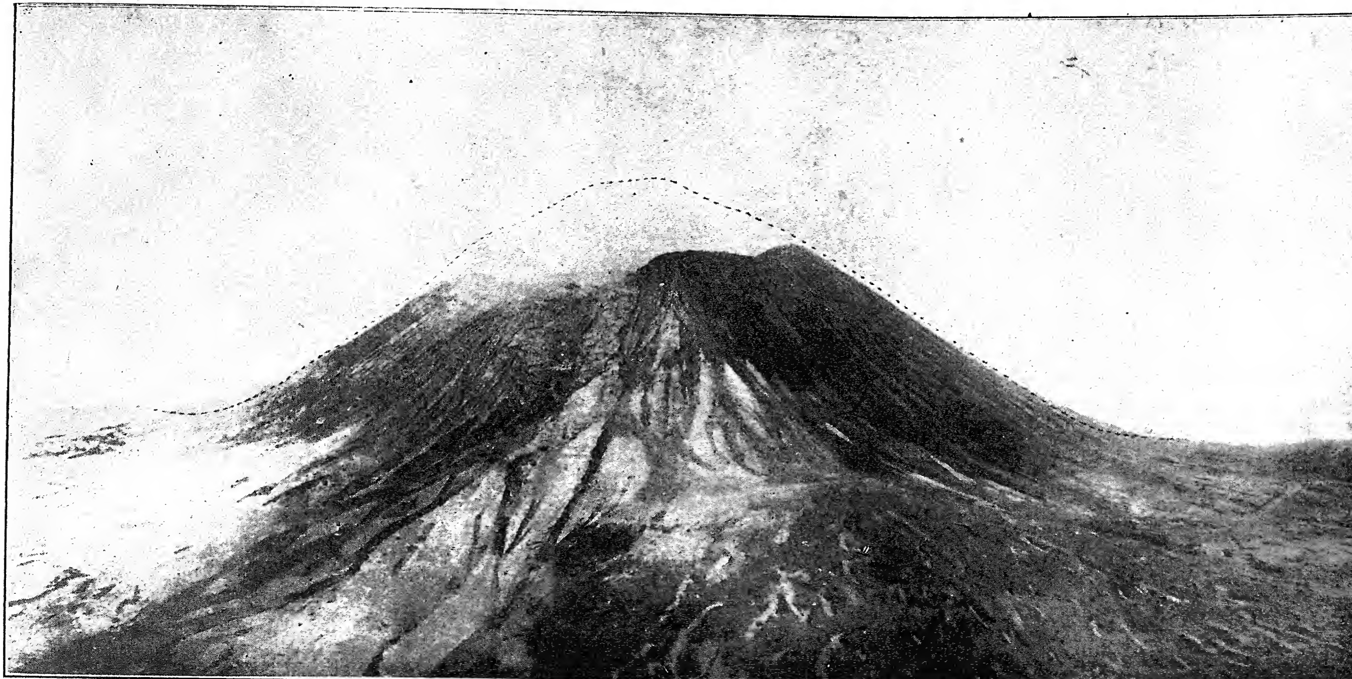


FIG. 76. — Furrowed and truncated cone of Vesuvius. (Courtesy of the American Geographical Society, Broadway at 156th St. From the *Geographical Review.*)

bind the entire mass together. Much of the consolidation of the fragmental material is also due to the fact that it falls often in a half-fused condition, and the heat from the volcano tends to bind the particles together. Material carried to greater distances, however, remains incoherent. Since the last eruption (1906) much gullying by erosion has occurred on the slopes of the cone (Fig. 76). (See also Fig. 86 *a*, p. 142.)

Etna

This famous volcano, in the eastern part of the island of Sicily, rises almost 11,000 feet above the sea, and has a nearly circular

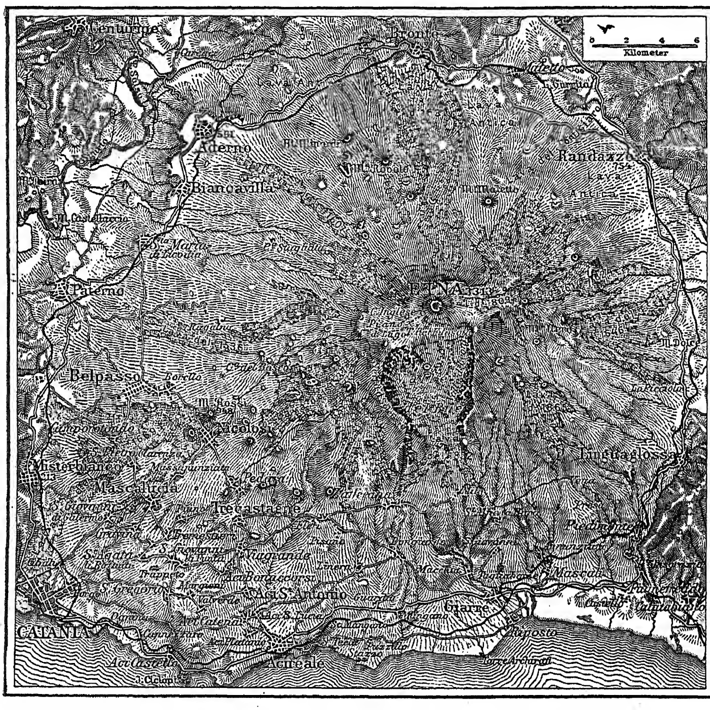


FIG. 77. — Map of Etna and the Val-del-Bove, or Valle-del-Bue. After map of Italian general staff. (From Ratzel.) The orientation of this map is such that north is on the right. The coast line runs in a direction east of north.

base with a circumference of 87 miles, while its lavas cover an area almost twice as great (Fig. 77). The lower part of the cone is cultivated; higher up are forests, and the upper part is a barren lava

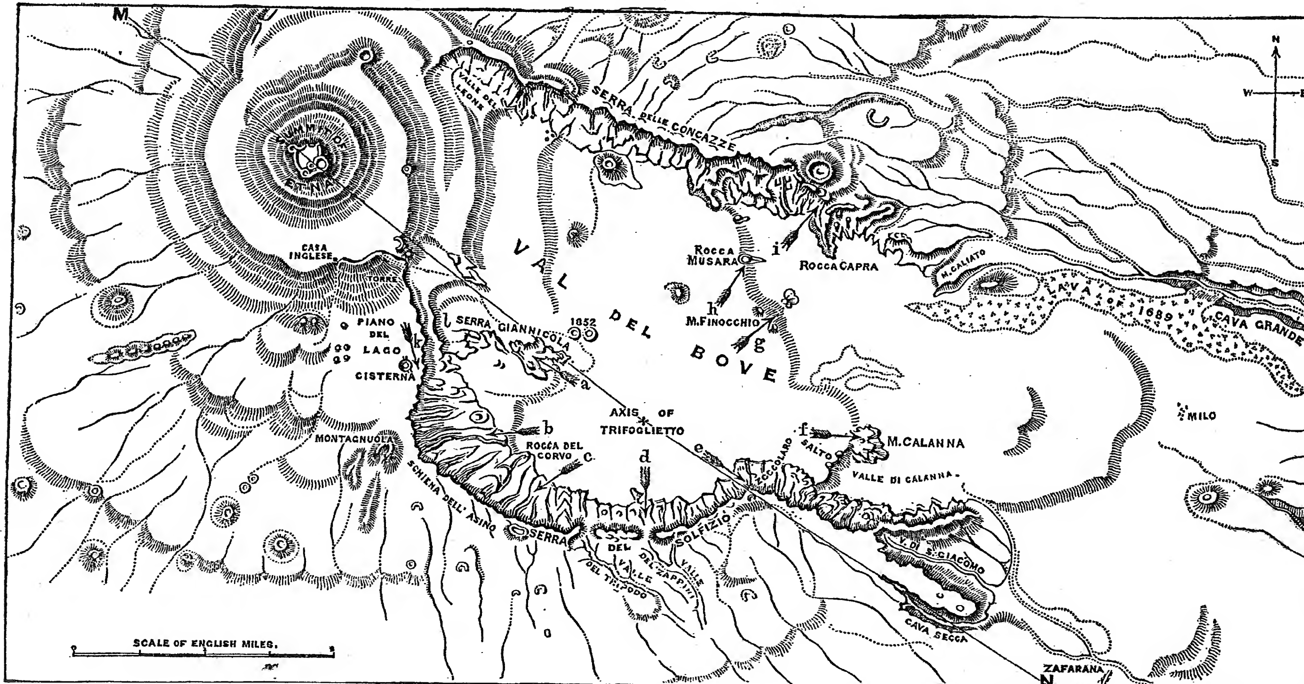


FIG. 78.—Map of the Val-del-Bove (Valle-del-Bue) and the cone of Etna, and a number of subsidiary cones or monticules. The arrows from a to k indicate the dip of the beds. (From Lyell's *Principles*.)

waste, which terminates in a sort of tableland, from which arises the principal cone, 1100 feet in height. From this cone sulphurous vapors and steam constantly arise, and lavas are emitted at frequent intervals. Viewed from north or south the cone is very symmetrical; but on the east it is cut by a deep valley, the *Val-del-Bove* or *Valle-del-Bue*, which is a vast amphitheater four or five miles in diameter, and is enclosed by precipices between 3000 and 4000 feet high at the upper end. This valley was probably formed in part by explosions and in part by subsidences (Fig. 78).

During the eruptions of Etna, which have been known to be more or less continuous since the fourth century B.C., the upper cone has repeatedly been blown away or has been partly engulfed by subsidences, being renewed again each time by upbuilding from lava and fragmental material. Where shown in sections, the structure is that of stratified layers dipping away steeply from the crater, but more complicated than in Vesuvius. Numerous dikes intersect the layers vertically and bind them together, such dikes being especially well shown in the walls of the Val-del-Bove (Fig. 79).

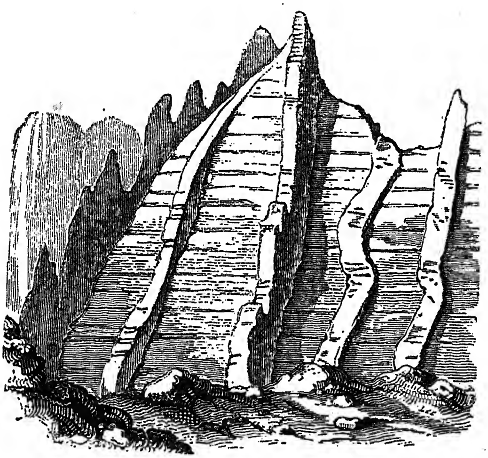


FIG. 79. — Dikes at the base of the Serra del Solfizio, Etna. (After Lyell.)

The formation of such dikes was illustrated by the eruption of 1669, when the whole top of the mountain collapsed. At this time a fissure six feet broad and of unknown depth opened in the side of the mountain, extending north and south for a length of 12 miles from the plain of St. Lio to within a mile of the summit. Five other parallel fissures opened one after the other. The incandescent glow from these fissures showed that they were filled up to a certain height with lava which on cooling produced transecting dikes. Near the town of Nicolosi, which lay near the base of the wooded

region, about 20 miles from the summit of Etna, and which was destroyed by preliminary earthquakes, a gulf opened from which sand and scoria were thrown, which built up a subordinate cone, *Monte Rossi*, about 450 feet high (see map, Fig. 77).

The great lava stream of this eruption overflowed fourteen towns and villages, some having a population of between 3000 and 4000 souls, and finally reached the walls of Catania by the sea (Fig. 77) 15 miles away. It accumulated against the walls of this city, which were 60 feet high, and finally flowed over them, but without

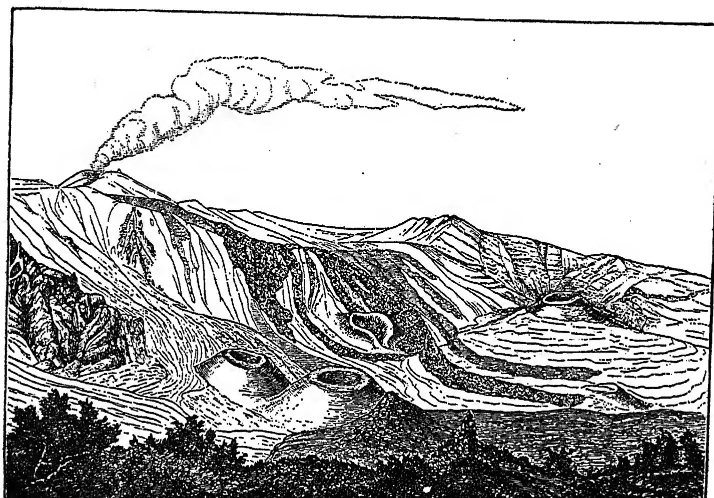


FIG. 80. — View of a part of the Val-del-Bove with parasitic cones and steep lava streams. The main crater, emitting steam, is in the background. (After Sartorius and Lasaulx, from Kayser's *Lehrbuch.*)

destroying them, falling on the inside in a series of fiery cascades which overwhelmed part of the city. It covered the first 13 miles of its journey in 20 days, but required 23 days for the last two miles. Sometimes it moved at the rate of 1500 feet an hour, at other times only a few yards in several days. When it finally reached the sea, it was still 600 yards broad and 40 feet deep. Its surface was generally solid rock, but the hot liquid interior broke this surface and flowed on to be in turn chilled with a repetition of the process. The course of this lava stream is shown upon the map (Fig. 77).

The formation of lateral cones or monticules from which two

eruptions proceed for every one that issues from the main cone, is a very characteristic feature of Etna, more than 200 such cones being known. One of these (Monte Minardo, east of Bronte, see map, Fig. 77) reached a height of over 750 feet. When new openings form, the lava from these may surround and even bury the old monticules, so that the volcano is covered with numerous, more or less buried, extinct, parasitic cones.

In the eruption of August, 1852, to May, 1853, two new cones opened close together near the head of the Val-del-Bove, rising in 16 days to a height of about 500 feet (Fig. 80). The lava poured down the Val-del-Bove, in places completely filling it from side to side, so that it became a barren waste, no longer able to support the cattle from which it had derived its name.

Mont Pelée

This volcano, on the island of Martinique in the West Indies, became violently active in May, 1902, the volcano Soufrière on St. Vincent going into activity at almost the same time. The eruption of Mont Pelée was characterized by violent explosions, pre-

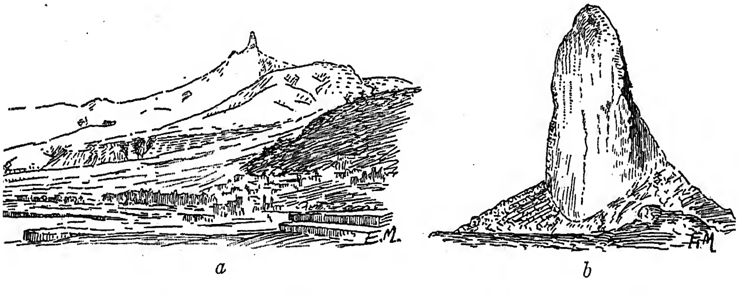


FIG. 81. — View of the volcano Mount Pelée, on Martinique, showing the spine (*a*) with a larger view of the same (*b*). (From E. de Martonne in *Géographie Physique*.)

ceded by small premonitory symptoms. There was no actual outpouring of lava, which was completely shattered, and the mass of minute, incandescent rock particles was carried aloft by the highly heated gases, forming dense fiery clouds, which not only rose into the air, but rushed like a stream through a gap in the crater down the slopes of the mountain into the sea, overwhelming and destroying all life, including all but two individuals of the 30,000 inhabit-

ants of the town of St. Pierre. This ejection of incandescent clouds continued for several months. Another remarkable feature of this eruption was the formation of the great spine, which will be again considered somewhat later (Figs. 81, 106, 107).

Krakatoa and Bandai-San

The volcano of Krakatoa forms an island in the straits of Sunda, between Java and Sumatra in the East Indies (Fig. 82). It suddenly became active on August 26 and 27, 1883. This activity

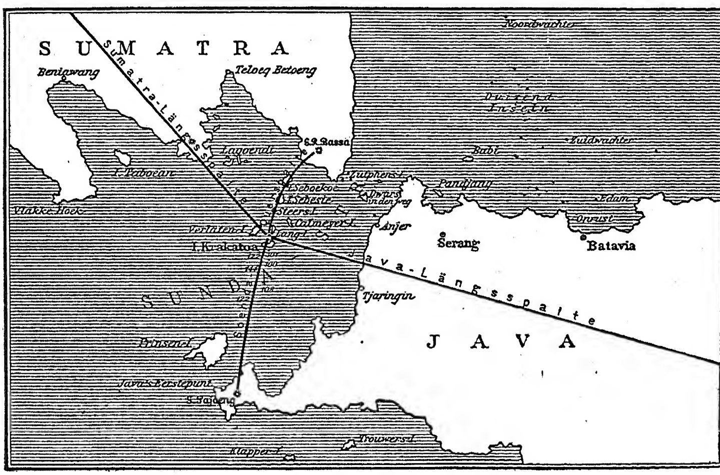


FIG. 82. — Map of the straits of Sunda in the East Indies, showing the location of the volcano Krakatoa and the rift lines which center in it. (After R. D. H. Verbeck, from Ratzel, *Die Erde.*)

began with a series of premonitory convulsions, after which the greater part of the island was blown away by a succession of terrific explosions, the detonations of which were heard more than 150 miles away. A mass of material estimated at a bulk of almost one and one-eighth cubic miles was thrown into the air in the form of lapilli, ashes, and the finest dust — some of it to the height of seventeen miles — and the air waves generated by the explosion traveled westward carrying the dust with them, and are supposed to have passed three and a quarter times around the earth (82,200 miles) before they died away. For many months after the eruption the dust in the air caused a series of brilliant sunsets all over the earth.

Dust fell in large quantities on the decks of vessels 1600 miles distant, three days after the eruption, and tracts of deep water were made so shallow from this dust as to become unnavigable. Great sea-waves (*tsunamis*) were generated, one of which was estimated

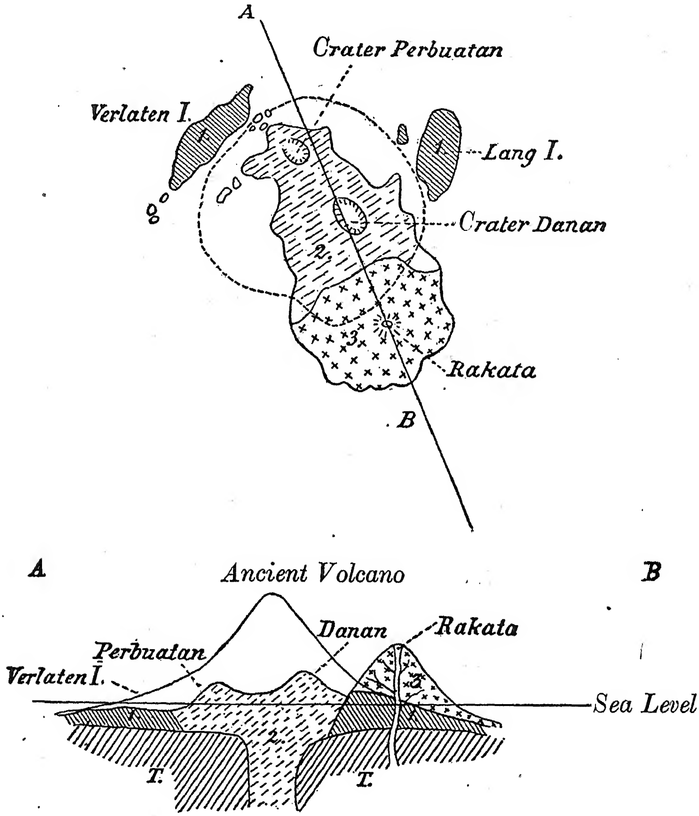


FIG. 83 *a*.—Map and section (on line *AB*) of Krakatoa before the explosion of 1883. After Verbeck. 1, older andesite; 2, younger andesite; 3, basalt; *T*, Tertiary basement. (From Kayser's *Lehrbuch*.)

to have risen 100 feet, and these destroyed 1295 towns and villages along the shores, killing 36,380 people. By their force a large ship was carried inland for a mile and a half and left stranded 30 feet above sea-level. Great blocks of stone, weighing from 30 to 50 tons, were also carried inland for two or three miles. Altogether this was the most stupendous manifestation of volcanic activity

known in modern times. The appearances before and after the explosion are shown in the maps and sections here given (Figs. 83 *a*, *b*) and the main remaining mass in Fig. 84.

Bandai-San in Japan was a volcanic cone 2000 feet high and had been dormant for a thousand years. Suddenly in 1888 the greater part of the cone was blown away by a terrific series of explosions

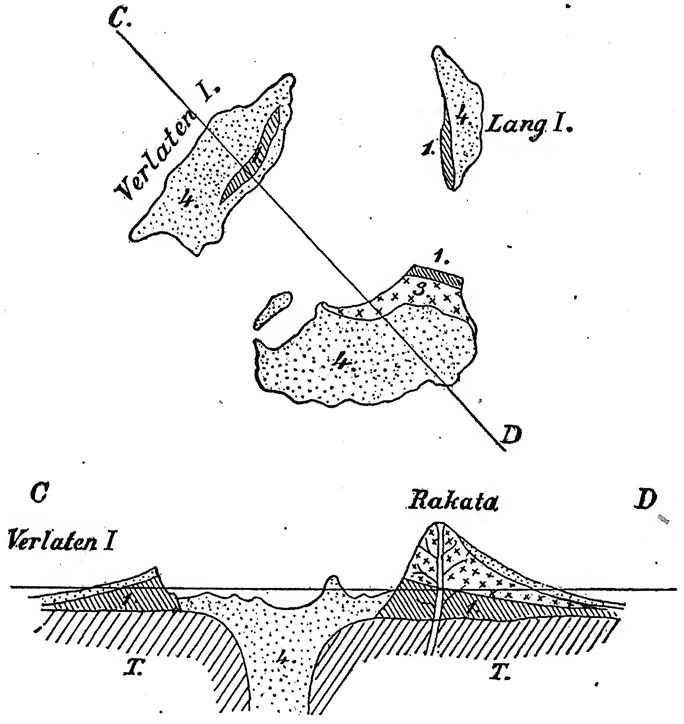


Fig. 83 *b*. — Map and section (on line *CD*) of Krakatoa after the explosion of 1883. 1 to 3, same as in preceding; 4, product of latest eruption. (From Kayser's *Lehrbuch.*)

which continued through a period of less than two hours, leaving only a remnant which terminates in a cliff about 1500 feet high (Fig. 85). This explosion is believed to have been due to the percolation of surface waters into the volcanic interior and the formation of steam, which caused the disruption. No lava flows were observed in this eruption, and the volcano has since been inactive.

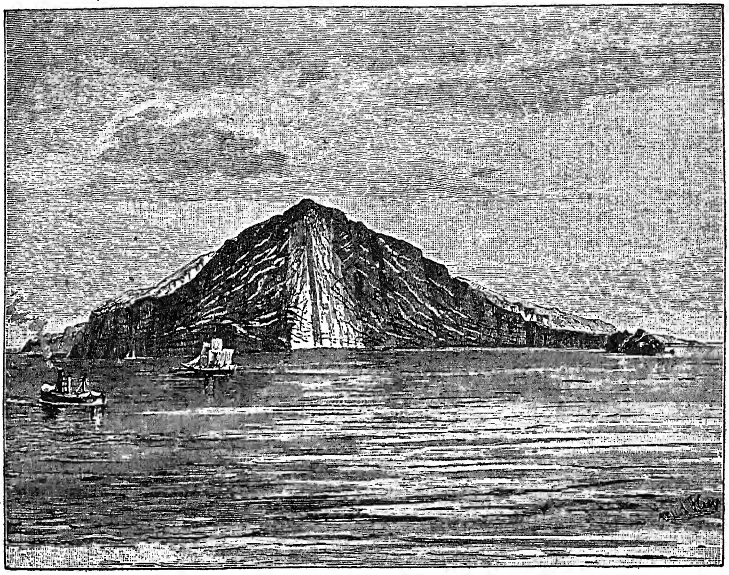


Fig. 84. — View of the Rakata of Krakatoa, the chief remaining fragment of an older eruption, showing the numerous dikes which bind the mass together. (After Judd from Ratzel, *Die Erde.*)

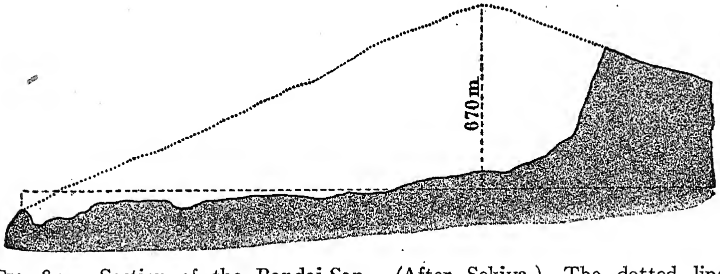


Fig. 85. — Section of the Bandai-San. (After Sekiya.) The dotted line shows the part destroyed by the explosion of 1888.

Classification of Volcanoes According to Type of Eruption and Form

We have now seen something of the mode of eruption of several distinct types of volcanoes in various parts of the earth. According to their mode of eruption, we may classify them as the *quiet type* on the one extreme, represented by the welling up and pouring out of liquid lavas, as in Kilauea, and the *explosive type*, represented by Krakatoa and Bandai-San, where shattering of

rock material occurs, but without the outpouring of liquid lava. In the milder examples of this type a cinder cone is built up (Figs. 86 *a*, *b*). Between these two stand the types which show both kinds of eruption, with the result that beds of volcanic ashes and lapilli alternate with beds of solidified lava. Here we place Vesu-

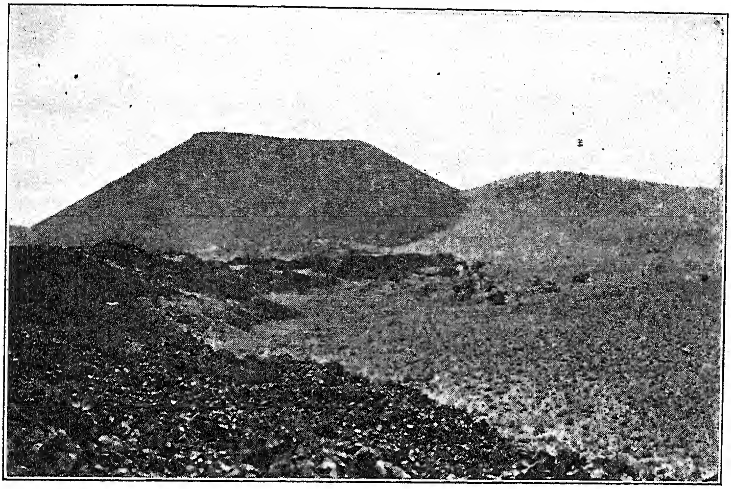


FIG. 86 *a*. — Cinder Cone, Arizona. Young cinder cone on left, late mature cinder cone on right. The young cone and lava flow are but a few hundred years old and are located on the northern edge of the Flagstaff, Arizona, topographic sheet. (Photo by D. W. Johnson.)

vius and Etna, explosive eruptions being more marked in the former and lava eruptions in the latter.

Comparison of Form. — Comparing the form of the cinder cone with that of a pure lava cone, we see a striking difference. The former, illustrated by the wonderfully perfect cinder cone of Mayon in the Philippines (Frontispiece) has steep slopes, the angle being determined by the nature and coarseness of the fragmental material. The lava cone, on the other hand, especially that composed of basic lava, is broad and relatively low, though the crater may be situated at a great height above the base. The slopes are very gentle, and the top generally a plateau. This is illustrated by Mauna Loa in the Hawaiian group.

In the diagrams on page 143 is shown a comparison of a number of modern volcanoes and craters drawn approximately to scale (Fig. 87).

Fig. 86 *b*.— The cinder cone at the summit of Mt. Vesuvius. This illustration shows the two types of material resulting from the eruption of Vesuvius. In the foreground is the hardened lava (igneous or pyrogenic rock), while the cone itself is built up of loose fragments, the cinders and ashes (pyroclastic material) which have resulted from shattering of the lava by the explosive eruption. The steep slopes of the side of the cone are characteristic of such rock. (After Stose; from U. S. G. S.)

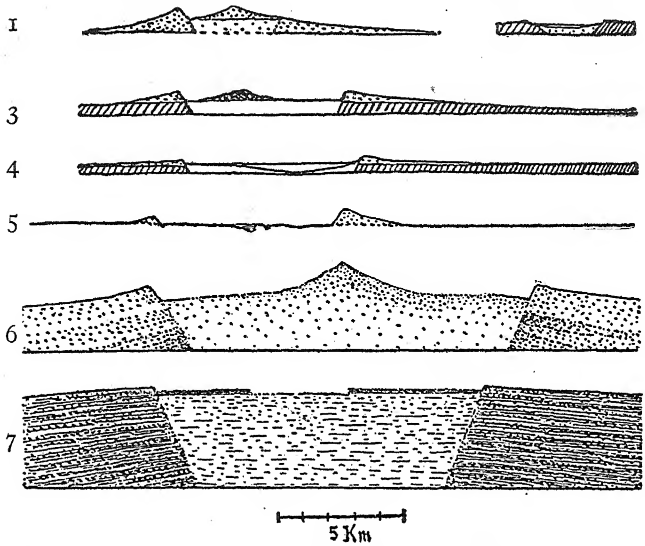


FIG. 87.—Cone sections of various types of volcanoes. 1. Vesuvius. 2. Lake Laach. 3. Rocca Monfina. 4. Lago Bracciano. 5. Krakatoa. 6. Peak of Teneriffe. 7. Mauna Loa. (From Kayser's *Lehrbuch*.)

GEOLOGICAL AGE OF VOLCANOES AND LAVA FLOWS

The geological age of a volcano can be determined from the age of the associated formations. It is obvious that a lava flow is always younger than the formation upon which it rests, and older than that which covers it. In Fig. 88 is shown a lava sheet which rests upon river gravels of Pleistocene age and is therefore younger than these. The extensive erosion which it has suffered, indicates that it is probably of late Pleistocene age.

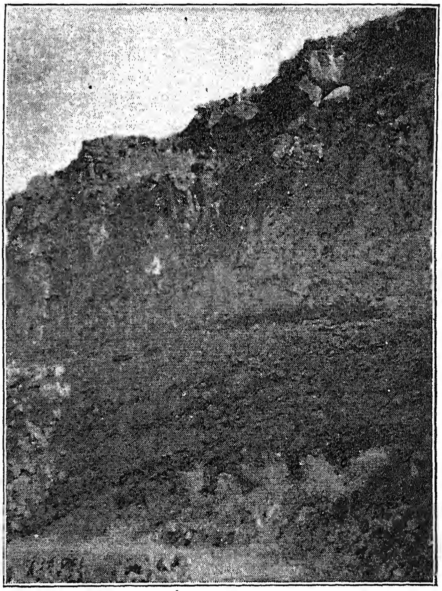


FIG. 88.—Lava flow over Pleistocene gravel, Utah. (Photo. by F. J. Pack.)

CHAPTER VIII

STRUCTURAL CHARACTERS OF VOLCANOES, AND OTHER IGNEOUS PHENOMENA

THE structural character of volcanoes is revealed in cones that have become extinct, for in these the parts are not only more easily accessible, but dissection has often revealed the internal character as well.

EXTINCT VOLCANOES

There are many regions where volcanoes have been active in the recent geological past, and in such cases enough of the form and character of the volcanoes, now extinct, is still retained to enable one to recognize them readily. Such recently extinct and partly dissected volcanoes are not only of interest as showing former distribution of volcanic activity, but they have an added value because their erosion has revealed many features which in an active volcano are not open to view. Thus the study of the recently extinct volcanoes supplements that of active ones.

Extinct Volcanoes of Central France

One of the most notable fields of former volcanic activity, and one that has played a prominent part in the history of the science of volcanology, lies in the central part of the great area of crystalline and younger rocks which makes up the so-called *Massif Central* of France, and which is bounded on the north by the Paris basin of Mesozoic and Tertiary rocks, on the southwest by the basin of the Garonne, and on the east by the valleys of the Rhone and Saône. The center of this massif (Fig. 89) is dissected by the river Allier, which flows north into the Loire, and it is along the western border of the Allier valley, which is bounded by a fault, that the main volcanic district is located, while a second one lies

on the southeast, in the region of the headwaters of the Allier and the Loire.

The younger eruptive rocks belong to several geological epochs, namely the Pleistocene, the Pliocene, and the Miocene. Of these the youngest, of Pleistocene age, form the famous *Chaîne des Puys*,

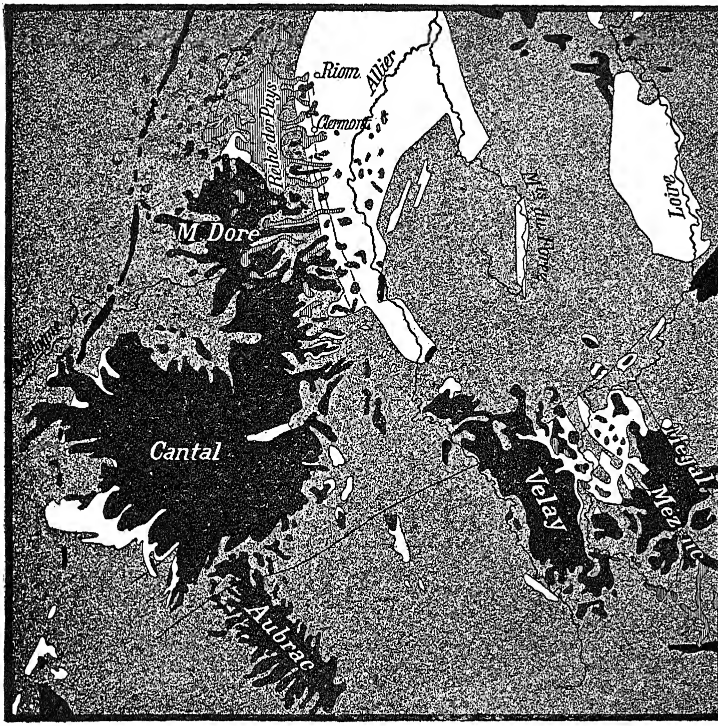


Fig. 89. — Geological map of Auvergne (after Michel-Lévy, M. Boule and Glangeaud). Scale about 1 : 1,400,000. Light gray, gneiss and granite. Black, Carbonic beds (mostly confined to the Loire valley). Dark gray, Tertiary trachytes, basalts, etc. Fine lines, Quaternary eruptives of the Puys. White, Tertiary and Quaternary. (From Kayser's *Lehrbuch.*)

a group of extinct volcanoes which still retain to a remarkable degree their form and general character. South of this lies the volcanic district of Mont Dore, and still farther south that of Cantal — both of Pliocene age. To the east of the latter and between the Allier and the Loire is the *Chaîne du Velay*, of Pliocene basalts, and east of this a series of Miocene eruptive hills (Mezenc and Megal).

The Chaîne des Puys. — This is best approached from Clermont-Ferrand, which lies to the east of the highest of these old volcanic hills, the Puy de Dôme (Fig. 90), from the summit of which an inspiring panorama of these silent volcanic cones, some sixty in number, may be seen. They extend for a distance of about 90 kilometers north from the Mont Dore region. The Puy de Dôme itself is not a perfect volcano, but is formed by a central dike or neck of trachytic rock (called by the French *domite*), but the great majority of the cones show each their cup-shaped crater at the top,

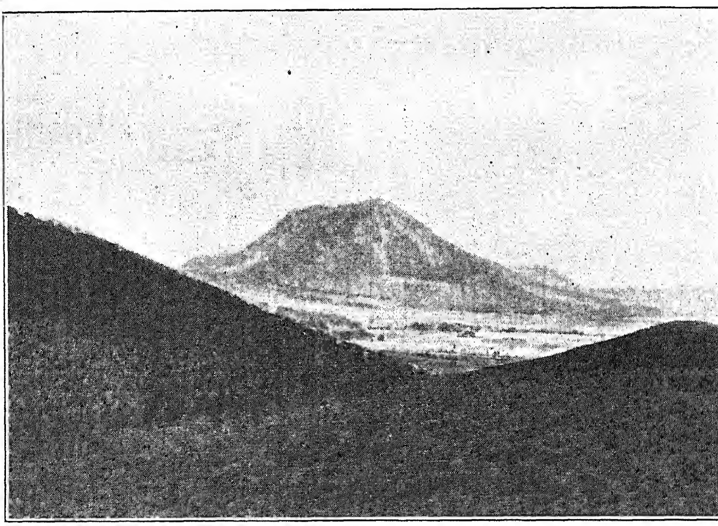


FIG. 90. — Puy de Dôme, an extinct volcano in the Chaîne des Puys, central France. (Photo. by D. W. Johnson.)

and produce a volcanic topography rivaling that of the surface of the moon (Fig. 91). The lava of these volcanoes consists of olivine basalts and andesites, with abundant slags, scoriæ, and pumaceous material all rich in ferro-magnesian minerals, and containing from 50 to 58 per cent of silica. The outpourings belong to the middle and later Pleistocene time. Besides the perfect crater cones there are, however, great intumescences, or dome-like blisters of trachytic rock without craters, and these represent the type of up-swellings of viscous acidic lavas already discussed. Such an one is the Grand Puy of Sarcoui, shown in the distance on the extreme right of our illustration (Fig. 91), and in outline on page 124 (Fig. 69 *a*).

The Massif of Mont Dore. — This mass, south of the Puys, represents the remnant of a great volcano, active during Pliocene time, but since then partly destroyed by erosion. While this makes

FIG. 91. — General view of the extinct volcanoes or Puys of Auvergne, France. (After Boule, Guide Congs. Int. Géol., France.)

possible the detailed study of the various parts of the volcano, and gives us an opportunity to observe the successive eruptions and their effects, it also makes a more difficult problem for the student to comprehend, for it must be borne in mind that the

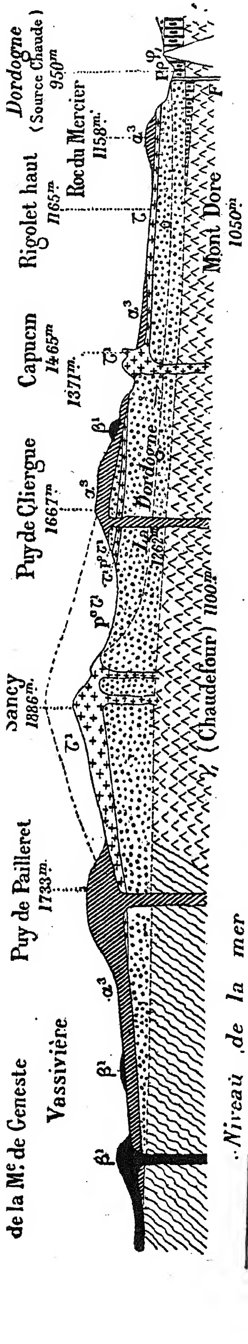


FIG. 92. — Section of the massif of Mont Dore, France, showing the succession of eruptions and the outline of the old volcano. (After Michel Lévy. Scale, 1 : 80000.) ζ^1, gneiss; γ, granite; Pρ, rhyolitic tuff; ψ, inferior phonolite; $p^0\tau^1$, andesitic tuff; τ^1, porphyritic trachite; α^3, hornblende andesite; β^1, plateau basalts.

many peaks and prominences now seen are not separate volcanoes as in the Puy district, but erosion remnants of larger masses, and the imagination must be drawn upon to restore again what is missing and so get a picture of the whole volcano as it was during its prime. In the adjoining diagram (Fig. 92) is represented such a view of the relationships of the different volcanic rocks which make up this volcano as would be obtained were the entire massif cut through its highest part (Sancy) like a round cake cut through the middle, and half of it removed so that the cut side of the other half is visible. Such a *cross-section*, as it is called, is built up from innumerable local observations which are then connected by logical inferences. This section shows that the foundation of the volcano is ancient granite and gneiss, and that it was built up on an almost level surface (a peneplane) which had previously been cut across the old foundation rocks by natural agencies. Upon this floor lies a mass of andesitic tuff, the product of the first eruptive activity (upper Miocene). Then (early Pliocene) followed an eruption of trachyte porphyries through the Sancy vents and that of the Capucin, the flows

of which extended laterally for some distance, finally thinning away. The next eruptions (middle Pliocene) were those of the Puy de Pailleret and the Puy de Cliergue on each side of Sancy, these lavas on cooling forming hornblendic andesites. Then came the late Pliocene eruption of the Plateau basalts, which cut and rest upon the others, and this was followed by local Pleistocene eruptions of the basalts and the formation of cinder cones which correspond to those of the Puy Chain. The succession of events is clearly indicated by the relationships, especially the superposition of the various lavas and pyroclastic products, and it will be observed that the eruptions proceeded from acidic trachytes (together with rhyolites, phonolites, etc.) to basic types, *i.e.* basalts. The tuffs often carry impressions of the vegetation of their time from which their geological age can be determined.

The Cantal. — This Tertiary volcanic massif lies south of Mont Dore and is connected with it by a basaltic plateau. It forms the most prominent of the Pliocene volcanoes, and it also shows much dissection, so that the structure and succession of eruptive events can be determined. Its diameter is from 60 to 80 kilometers, and its mass about ten times that of Mont Dore. As in the latter case there are many elevated peaks, the highest of which, the Plomb-du-Cantal, rises 1858 meters. These are all erosion peaks of parts of older eruptions, only one — the Puy de Griou (1694 meters) — representing a late, though not the latest, eruption from the center of the volcano, but even it does not show the original height of the mountain. In Fig. 93 two cross sections are shown, one from northwest to southeast, the other at right angles to it, and both passing through the center of the old volcano. These are reconstructed in the same manner as that of Mont Dore, namely, from numerous local observations and the combination of these. The succession of eruptive events here is of similar character to that of Mont Dore, the volcano resting upon an old erosion floor of gneiss upon which were locally deposited beds of Oligocene sediments (4, Fig. 93), which are especially well shown on the southwest. Through these came, first, eruptions of older basalt (5) (not positively known, though suspected, at Mont Dore) and this was followed by eruptions of acid trachytes and phonolites with trachytic tuffs, still of Miocene age (6). These locally rest upon the gneiss, or upon the Oligocene sediments, and still again, in one part of the section, upon the older basalts, showing that they

succeeded these. Then was thrown out from the central orifice a mass of breccias, cinders, etc., of andesitic and basaltic material (7), intruded by dikes and interbedded with sheets of andesite,

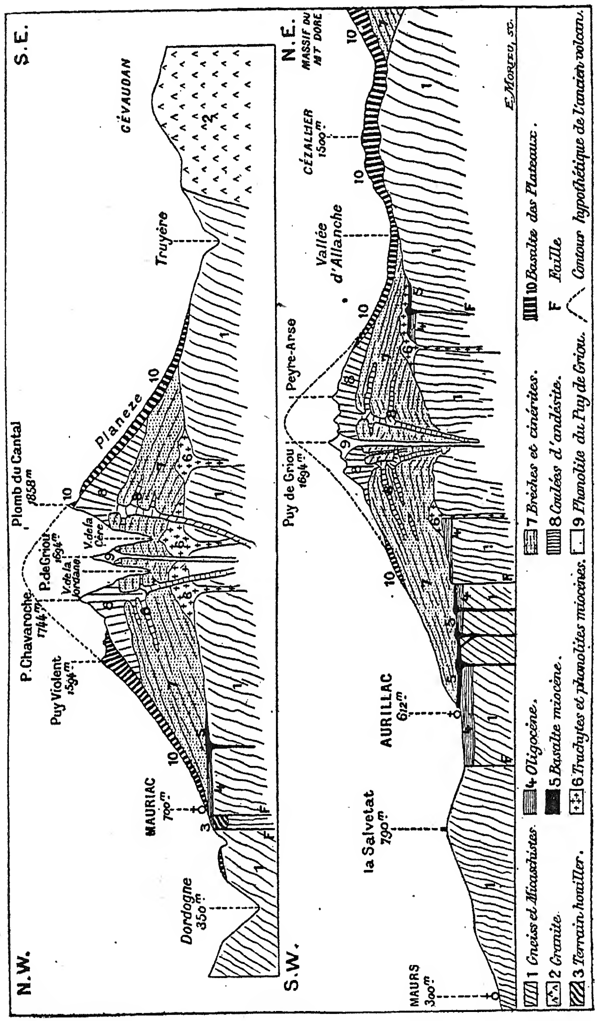


FIG. 93.—N. W.–S. E. section (upper) and S. W.–N. E. section (lower) of the Cantal district of France, showing the reconstruction of the old volcano with its succession of lava flows. 1, gneiss and mica schist; 2, granite; 3, Carbonic beds; 4, Oligocene; 5, Miocene basalt; 6, Miocene trachytes and phonolites; 7, breccias and tuffs; 8, interbedded andesites; 9, phonolites of the Puy de Griou; 10, plateau basalts; F, faults. The hypothetic contour of the old volcano is represented by dotted lines. (After Marcellin Boule.)

this also forming a capping rock (8) and marking the great early Pliocene eruption from the central orifice. Through these, in middle Pliocene time, was forced the dike of phonolite which forms the Puy de Griou, and finally came the eruption of the last basalt,

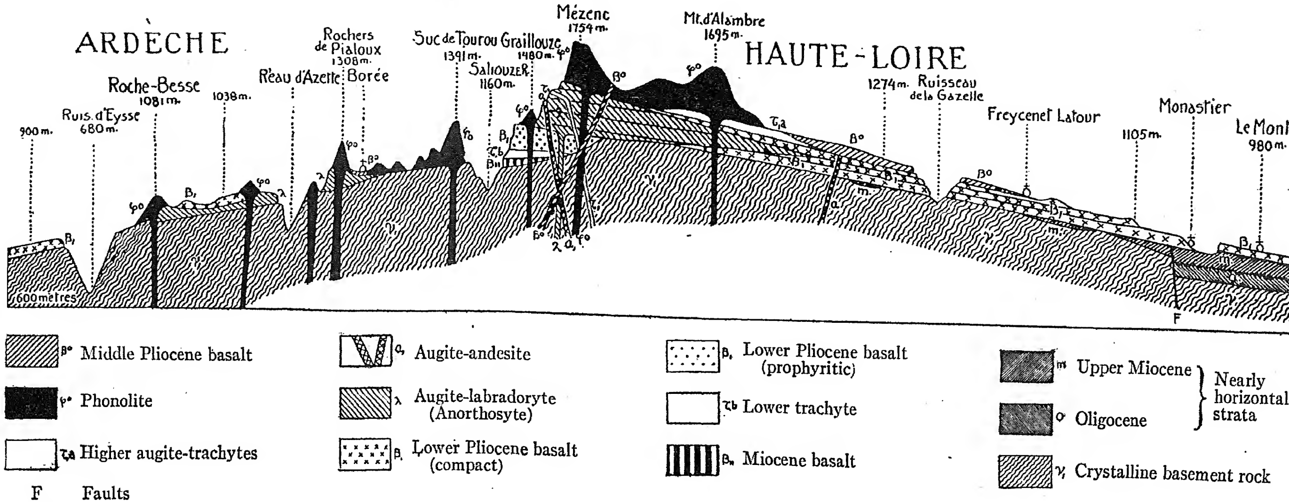


FIG. 94. — General view, in part schematic, of the volcanic massif of the Mézenc. (Redrawn after M. Boule, 8th Int. Geol. Congr. Guide X.) The Oligocene (o) and Miocene (m) strata should have been represented as horizontal. Basement line = 600 meters above sea-level. The section is drawn with the observer looking southwest. The left end of the section is southeast, the right, northwest.

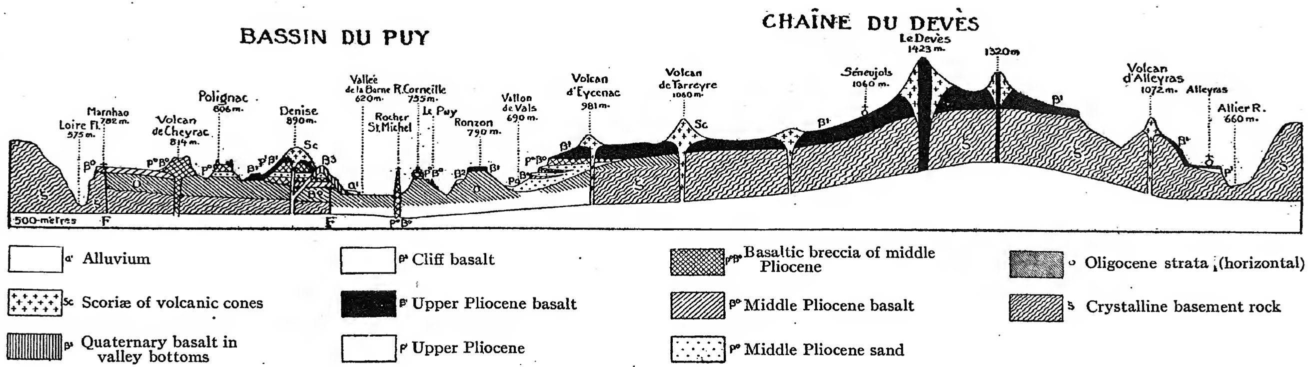


FIG. 95.—General view, in part schematic, of the "Bassin du Puy" and the "Chaîne du Velay" or "Chaîne du Devès," Central France. (Redrawn after M. Boule, 8th Int. Geol. Congr. Guide X.) The Oligocene strata (*o*) should have been represented by horizontal lines. Basement line, 500 meters above the sea-level. The section is drawn with the observer looking to the southeast; thus the left end of the section is northeast and the right-end southwest. Compare maps Figs. 89 and 96.

the so-called Plateau basalt, because the great plateaus of the region are capped by it.

If the student has succeeded in gaining a clear conception of the succession of events in these two dissected volcanoes, he may next attempt an analysis of the two cross sections of the southeastern district given in the next two diagrams (Figs. 94 and 95), where, as a result of eruption through numerous vents, a more complicated structure is produced. After this he will be ready to analyze

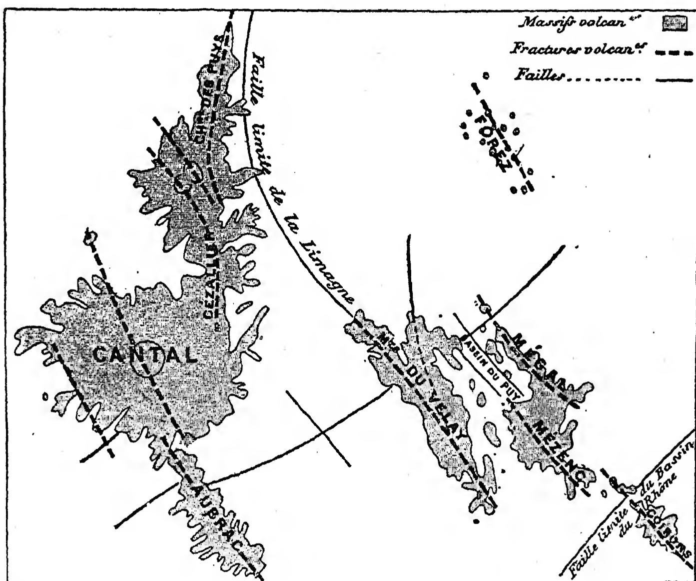


FIG. 96. — Map of the volcanic areas and fracture lines of Central France, the former shaded, the latter in broken lines. Fault lines are shown solid. (After Marcellin Boule.)

sections of older volcanic districts, including those of our own country, as given in the various folios of the *Geological Atlas of the United States*.

Arrangement of these Volcanic Centers Along Lines of Fracture in the Earth's Crust. — From the study of the volcanic region of Central France it has become apparent that all of these volcanic manifestations are located along lines of fracture in the earth's crust, these fractures making possible the rise of the lavas and gases which have produced the phenomena. The map of the region (Fig. 96) shows the fractures ascertained and their relation

to the volcanic manifestations. This is a very general arrangement of volcanoes the world over, and will be referred to again later on.

The Extinct Volcanoes of the Rhine Region

Extinct volcanoes and volcanic activity during Tertiary time are shown in a number of localities in the mountainous region through which the river Rhine has cut its famous gorge. The most impressive of these are the Seven Mountains (Siebengebirge)

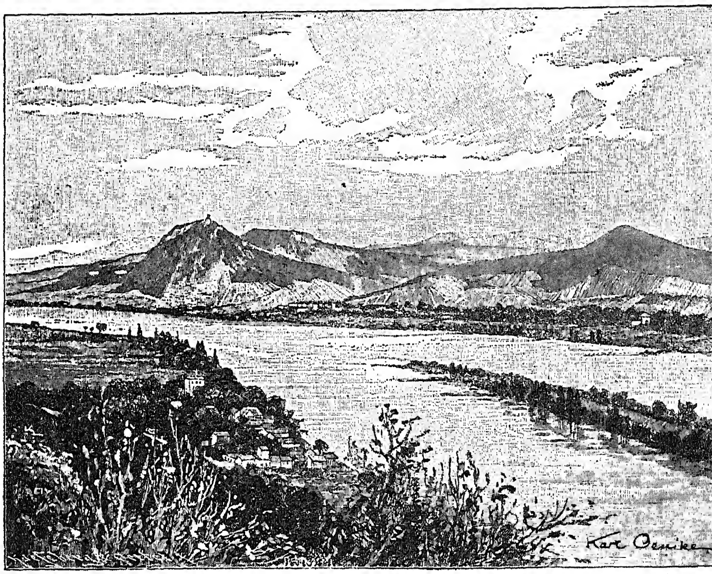


FIG. 97. — Volcanic landscape of the Siebengebirge after a photograph from the Rodderberg. (From F. Ratzel, *Die Erde.*) These low mountains are slightly dissected volcanic peaks of Tertiary age. The high peak on the left is the Drachenfels. (See map, Fig. 98.)

on the right bank of the river in the Cologne region not far from Bonn (Fig. 97). Like the Tertiary volcanoes of France, these show only in part their former character, erosion having modified them to a considerable degree. Nevertheless, it can be recognized that they represent a series of eruptions, which, like those of France, proceeded from acidic to basic lavas.

The eruptions began in Miocene time, and the volcanic masses were built up on the old erosion surface of the Devonian shales

and sandstones, which form the cliff of the Rhine gorge (map, Fig. 98). The first outpouring resulted in the formation of light-colored trachyte of which the typical trachyte of the Drachenfels, already referred to in the discussion of that rock (p. 101), was the product. Others of the hills of this region were also formed by this

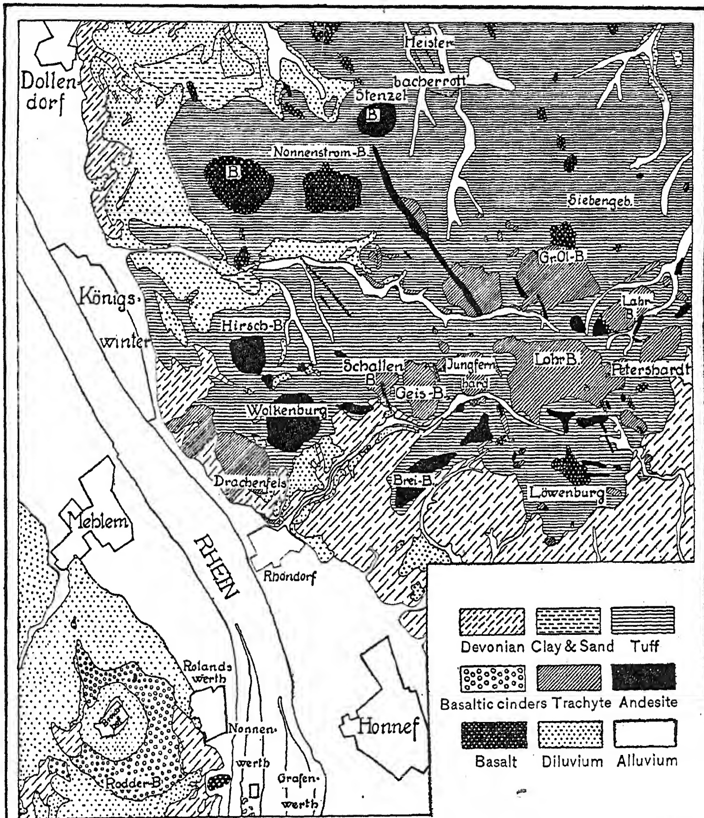


FIG. 98. — Map of the volcanic district of the Rhine (Siebengebirge). (After Laspeyres, from Walther.)

eruption. The next eruption was of more basic lava, resulting in the formation of andesites, of which rock another group of these hills is composed. Finally, very basic lavas came to the surface, forming basalts, the hills of this rock being scattered among the others, while dikes of the basalt cut the older andesites and trachytes. This last eruption occurred in Pleistocene time. There is thus a

succession from acid to basic lavas as in the Auvergne district. One of the last formed of these volcanoes is the Rodderberg, situated on the west bank of the Rhine between Mehlem and Rolandseck. It consists of basaltic scoriæ which in places rest upon, and have by their heat altered and partly fused, some of the older river sediments of the Rhine, and its crater, still perfectly recognizable, is filled with a deposit of wind-blown dust or *loess* and has now become the site of a thriving farm (the Broichhof).

Extinct Calderas and Sinks

The term caldera has often been applied to large craters, such as those of Kilauea, but it has recently been suggested that these

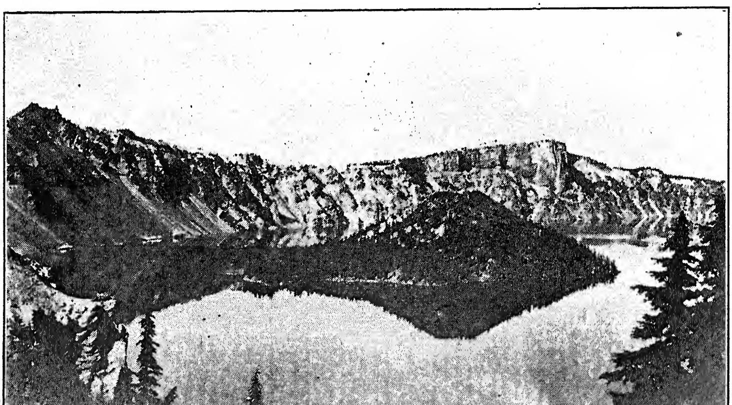


Fig. 99. — Cinder Cone within the Crater Lake, Oregon. A volcano built within the basin of a sink. (Photo by D. W. Johnson.)

be spoken of as *sinks*, because they are formed by subsidences of the lava column, and that the name *caldera* be restricted to explosion craters or hollows such as that formed at Krakatoa (Daly). Both sinks and calderas are known which were formed by past volcanic activities in a region not subject to such disturbances at present. An example of an older sink is Crater Lake, Oregon (Figs. 99, 100 *a-d*). This occupies the site of a former volcano, which has been named Mount Mazama (Fig. 100 *d*) and the summit of which has collapsed. From this summit glaciers descended probably during the Pleistocene glacial period, which scoured and polished the sides of the volcano, as is shown by the marks still

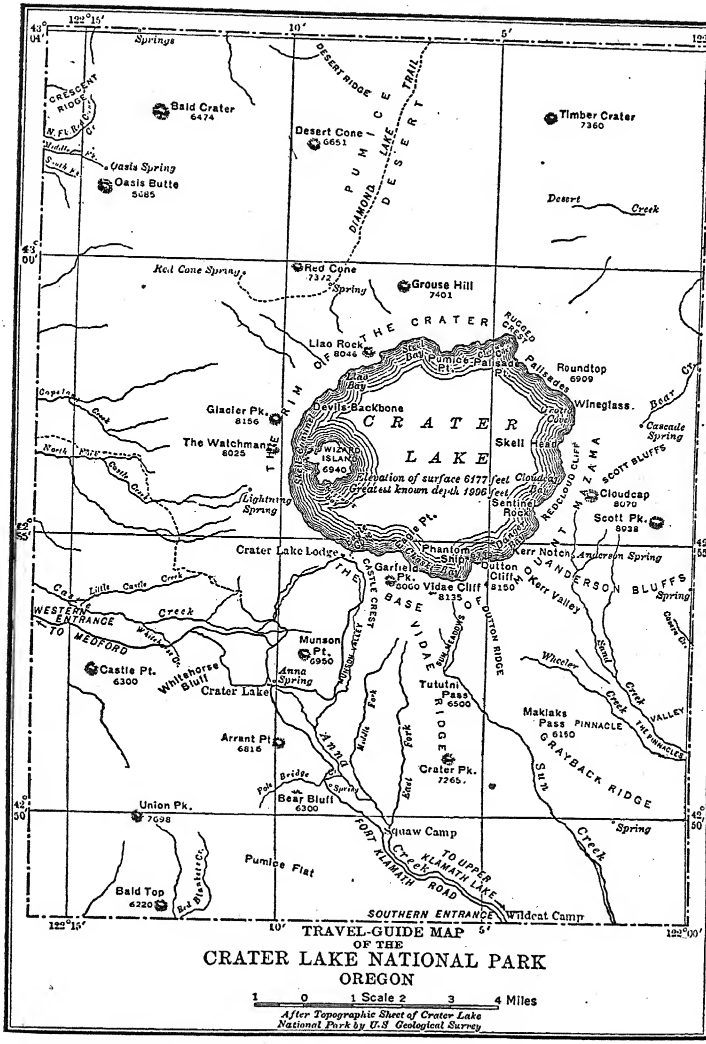


FIG. 100 *a.* — Map of Crater Lake, National Park, Oregon. (U. S. G. S.)

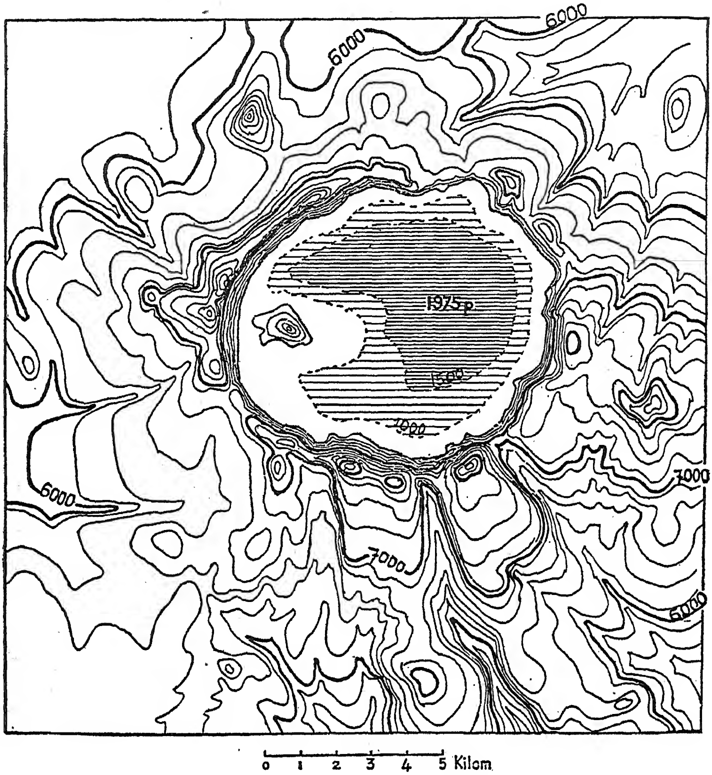


FIG. 100 *b*. — Map of Crater Lake, Oregon. (U. S. G. S.) Heights and soundings in feet. (Copied from de Martonne.)

remaining on the outer slopes of the lake rim. Thus the collapse of the mountain summit is shown to have been a recent one, and appears to have followed upon an extensive outpouring of

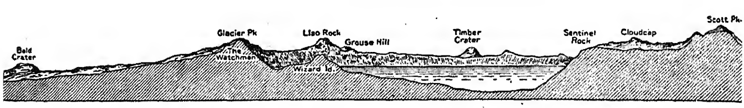


FIG. 100 *c*. — Profile section of Crater Lake National Park. (U. S. Dept. Interior.)

lava. Many old calderas are found in various parts of the world, those of the Eifel district in western Germany (Fig. 101), where they are known as Maare, being the most typical (Figs. 102, 103). These are readily recognized by their circular character,

and by the fact that around their margins are extensive deposits of scoriæ and even of small volcanic bombs together with the fragments of shale and sandstone blown from the craters (Fig. 104). Less frequently are lava flows of basalt trachyte or

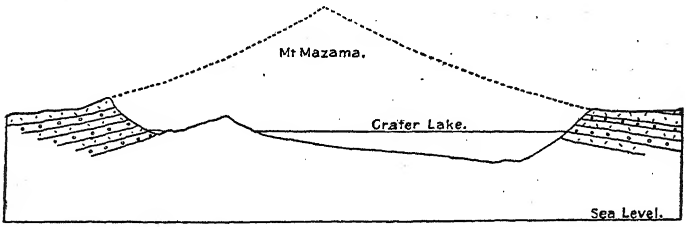


FIG. 100 *d.* — Section of Crater Lake and its rim, with the probable outline of Mount Mazama. Structural details generalized. (Vertical and horizontal scale the same.) Smithsonian Institution.

phonolite associated with them, which, together with the fragmental material, built up crater cones. One of the most typical and largest of these hollows is now occupied by the beautiful Laacher Lake (Fig. 105). The lapilli from these explosive eruptions form

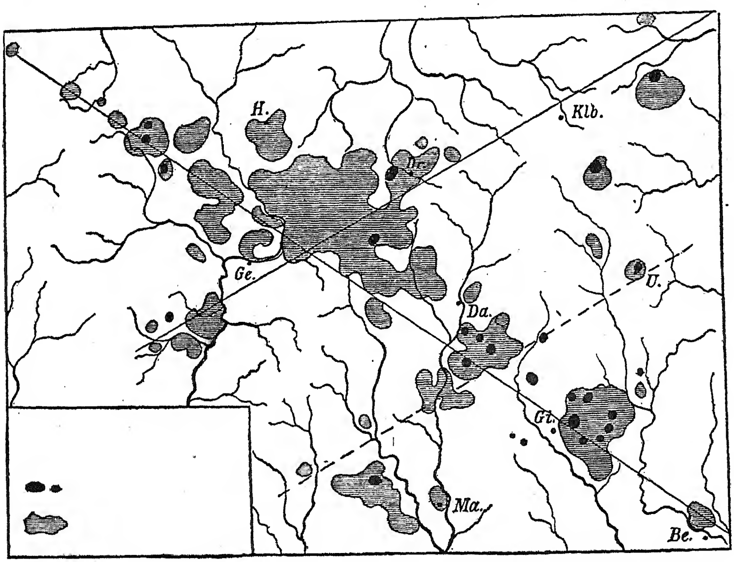


FIG. 101. — Map of the volcanic district of the Eifel. (After von Deschen.) Be. Bertrich; Da. Daun; Dr. Dires; Ge. Gerolstein; Gi. Gillenfeld; H. Hillesheim; Klb. Kelberg; Ma. Manderscheid; U. Ulman; Maare in black; volcanic rocks, shaded. (From Kayser's *Lehrbuch.*)

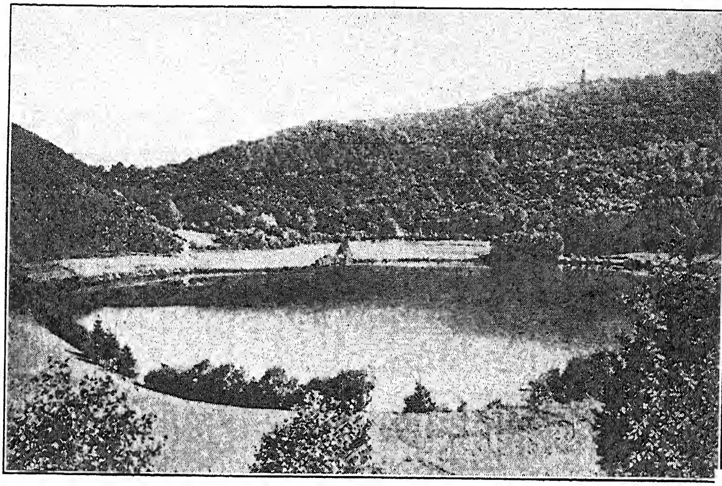


Fig. 102. — Gmünden Maar, Eifel.
An explosion crater converted into a lake.

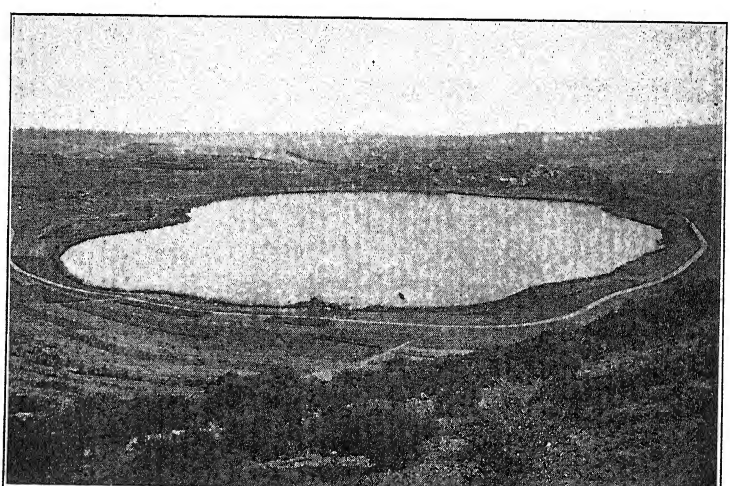


Fig. 103. — Schalkenmehren Maar, Eifel.
A Tertiary explosion crater converted into a lake.

extensive deposits of "sand" along the left bank of the Rhine, readily visible from the train.

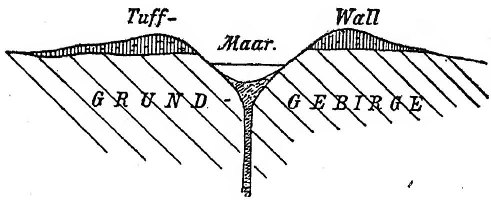


FIG. 104. — Ideal section through a Maar of the Eifel showing the old crater funnel and pipe, with the lakelet in the upper part, and the wall of tuff and scoriæ surrounding it. (From Kayser's *Lehrbuch.*)

VOLCANIC FUNNELS AND PIPES, SPINES, PLUGS, AND NECKS

Funnels and Pipes. — From the mouth or rim of the crater of the volcano the slope is generally inward, forming a funnel-shaped depression to its bottom, this constituting the normal crater. This differs from the crater of Kilauea, which is a *sink* with practically perpendicular sides. The funnel is continued

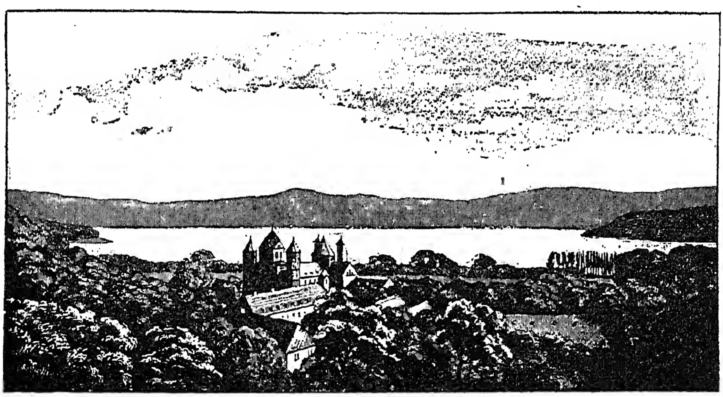


FIG. 105. — The Laachersee (Lake Laach) Northwest Germany, occupying an old explosion crater. (After Walther.)

downward into the depths of the earth's crust as a more or less cylindrical tube or *pipe*, which is the main conduit or vent through which the lava reaches the surface. (See Fig. 87, p. 143.)

The Spine of Mont Pelée (Figs. 106, 107). — We have, of course, no direct means of knowing from observation that this tube

is in reality a cylindrical one, nor that it penetrates vertically through the country rock upon which the volcano is built. That such is the case, however, may be inferred from the remarkable phenomenon which accompanied the eruption of Mont Pelée in Martinique

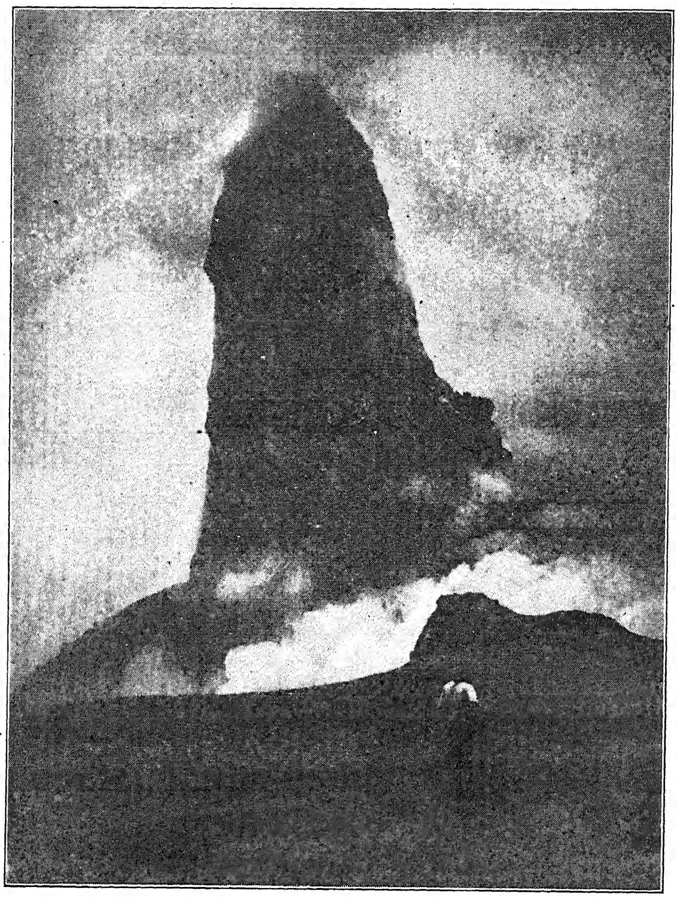


FIG. 106. — The great "spine" of Mont Pelée, Martinique, from the east. From the old summit plateau, the basin of L'Etang Sec. The spine rises approximately 358 meters above the old crater rim in the middle foreground. (Photo by E. O. Hovey, March 25, 1903; courtesy of American Museum of Natural History.)

in 1902, when a columnar mass of extremely viscous or solid lava was pushed up 700 to 1000 feet above the crater, reaching a height of over 5000 feet above the level of the sea. This remarkable

column appears to have been the *plug* of lava which filled the pipe of the volcano, and which lacked the proper fluidity to flow over the edge of the crater, but hardened in the pipe and was pushed upward by the pressure of the gases beneath, retaining essentially the form of the tube in which it had solidified. The growth of this spine of Mont Pelée was actually witnessed. It began in October, 1902, and reached its maximum elevation in seven months. After that it slowly crumbled away under the influence of the

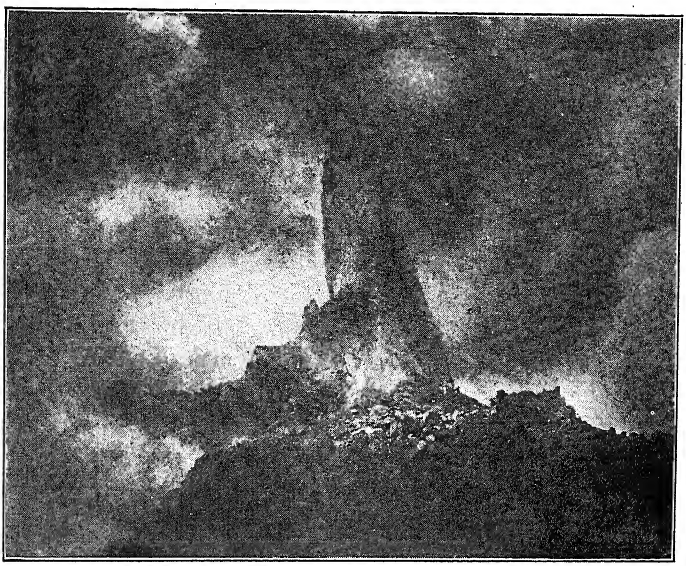


FIG. 107. — The spine and upper part of the new cone of Mont Pelée, Martinique, from the north; from the crater rim. (Photo by E. O. Hovey, March 26, 1903; courtesy of American Museum of Natural History.)

atmosphere and its own weight, and from the explosion of gases beneath it.

Plugs and Necks. — If we speak of the tube which descends from the base of the crater as the *volcanic pipe* or *vent*, the solidification of the lava in this pipe forms the *volcanic plug*. When this plug is pushed upward and becomes visible, as in Mont Pelée, it constitutes a *volcanic spine*. When it becomes visible as the result of the removal of the enclosing mass of the rock material which constituted the volcanic cone, it becomes a *volcanic neck*. Necks are often left as the only relief feature of a volcano, because of the

solid nature of the lava which has hardened in the tube or pipe, and the more readily erodible character of the material which constitutes the rest of the volcano. Frequently, too, a cross-section of a plug still within the pipe is seen when the country has been worn down until both volcano and projecting neck have been removed. Again, in an erosion cliff, a vertical section of a part of such a volcanic plug may sometimes be seen, showing the relation which it assumed to the country rock on cooling. From such sections the form of the plug, and hence that of the original pipe, may be ascertained. Theoretical considerations, too, would lead us to infer, first that the upward path of the heated gases, vapors, and lavas is most likely a direct one, and secondly that the passage-way would become a more or less cylindrical one, even though it was part of an irregular fissure in the first place.

The French experimental geologist, Daubrée, was able to show that gases and vapors under high pressure, when forced through fissures in limestone, granite, steel, or other substances, converted their passageway into a cylindrical canal. From this we may argue that the pipe or passageway of some volcanoes was formed by the advancing heated gases and vapors which are liberated from the magma deep down in the earth, and which, under a pressure of thousands of atmospheres, are forced to find their way to the surface through fissures, which they enlarge to cylindrical canals and thus prepare the way for the uprising lava masses.

Volcanic Necks and Exposed Plugs of Old Volcanoes

As we have seen, the term *volcanic neck* is applied to the hardened mass of lava which filled the upper part of the pipe of the volcano and which has been modeled out in relief by the erosion of the material of the cone which formerly surrounded it. This is to be distinguished from a *volcanic plug*, which is the mass of lava hardened in the pipe which is seen to be still surrounded by the material through which it passed, whether this is the material of the cone, or the country rock beneath, on which the volcano was built up.

In districts of comparatively recent but extinct volcanic activity, volcanic necks are not uncommon. Some of the finest examples

are found in the Tertiary volcanic district of Haute-Loire, France, the eastern part of the volcanic region of Auvergne already referred to. Here, near the town of Le Puy, is the famous Rocher St. Michel (Fig. 108), an almost perfect example of a volcanic neck from which all surrounding material of the cone has been removed. This old neck, the position of which is shown in the section on p. 152 (Fig. 95), is not a uniform mass of lava, however, but is rather

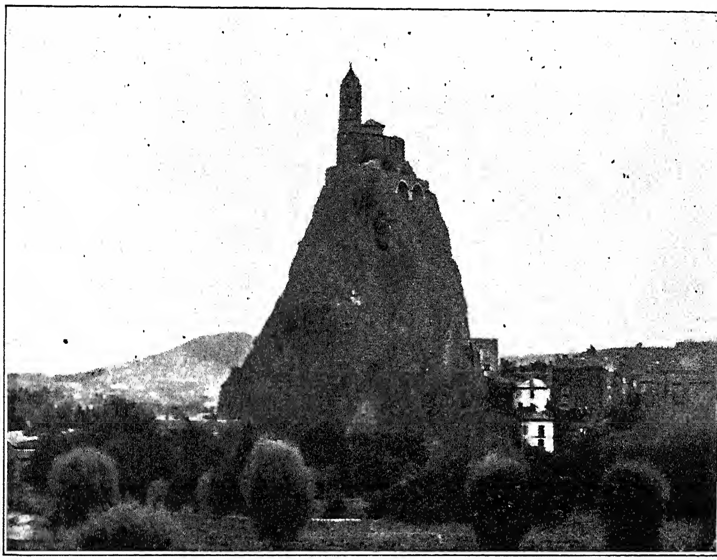


FIG. 108. — Rocher St. Michel, in the Bassin du Puy, south central France. The modeled-out neck of an extinct volcano, now crowned by a chapel. For location and relation to other rocks of the region, see the section, Fig. 95, page 152. (After Tempest Anderson, *Volcanic Studies in Many Lands.*)

made up of fragments of volcanic rock bound together by igneous material, and represents the product of an explosive eruption, the fragments having fallen back again into the throat of the volcano where they were solidified. Thus this neck represents the filling of the upper part of the old volcanic vent, and although it no longer shows the perfect original form of this vent, having been subjected to narrowing by erosion near the top, it may still be regarded as nearly typical of such structures. Its summit is to-day crowned by a chapel. The neighboring and higher Rocher Corneille is, however, an erosion remnant of a brecciated lava mass,

probably from this same volcano, and rests on horizontal strata (Oligocene).

Typical examples of volcanic necks from our own country are the Leucite Hills of Wyoming, and peaks of the Mount Taylor region of New Mexico (Fig. 109). Another example, from Colorado, is shown in Fig. 110. In diameter such necks may vary from several hundred feet to several miles, and the material may be either solid lava or fragments of the same bound together, that is, a breccia of lava fragments. When the necks have been exposed to atmospheric influences for some time, especially in a dry climate, they

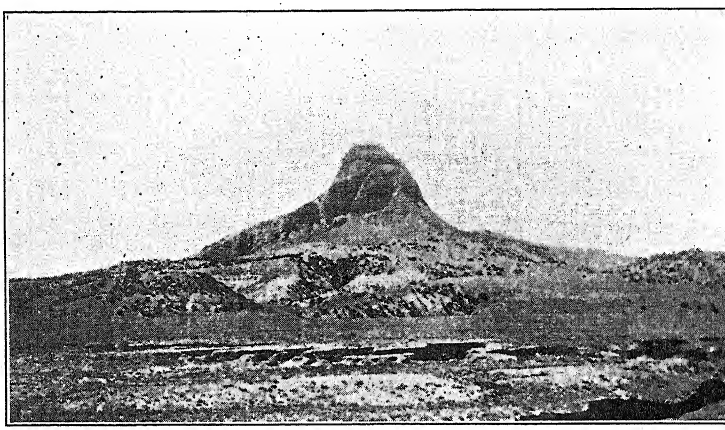


FIG. 109. — Great Neck, a volcanic neck in the Mount Taylor region, New Mexico. (Photo by D. W. Johnson.)

are apt to crumble, and a mass of loose débris will accumulate around them, forming a conical hill or tepee butte, from which the summit of the much reduced neck may project. Such a hill must not be mistaken for the original volcanic cone which surrounded the central plug of lava before it was modeled out in relief as a neck. It is merely a conical heap of fragmental material forming talus-slopes around the central core, from the destruction of which the material was derived.

Not all projecting neck-like masses of volcanic rock, however, can be interpreted as old volcanic necks. We have already seen that the Rocher Corneille at Le Puy, France, is an erosion remnant of a brecciated lava sheet resting on older rocks, although its form is not unlike that of the old neck of the Rocher St. Michel close by (see Fig. 95). The famous Devil's Tower, or Mato Tepee, of

Wyoming (Fig. 111) has long been, and by some is still, regarded as an ancient volcanic neck, but others consider it as a tower-like erosion remnant of an old lava sheet intruded beneath the surface (probably a laccolith, see beyond). The peculiar columnar structure of the rock of this tower favors the last interpretation, as will be more fully shown in the next chapter. The determination of the neck character of such a mass depends, of course, on the possibility of showing that the igneous rock continues downward through the rocks of the earth's crust, whereas an erosion remnant of a lava sheet or intruded mass would rest upon the

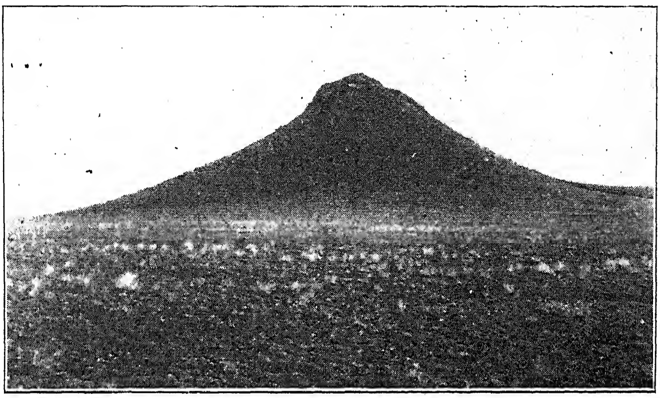


FIG. 110. — Conical butte formed by a typical volcanic plug, — a pillar of basalt formed by cooling in the vent of an extinct volcano, and modeled out in relief as a neck by erosion of the volcanic material which formerly surrounded it. It is now surrounded by basaltic débris due to weathering, and this forms talus-slopes. One mile north of Adair station, Colorado and Southern R. R. Elmoro quadrangle. Colorado. (G. W. Stose, photo from U. S. G. S.)

rocks of the crust which are continuous beneath it, and would not necessarily have direct connection with the deeper parts of the earth.

Volcanic plugs, *i.e.*, the hardened lava which still fills the old pipes, are exposed in many regions in horizontal or in vertical sections as the result of erosion. Practically all of these are found, not within the old volcanic cone, for sections of such cones are seldom if ever exposed, but in the rock beneath, upon which the now vanished volcano had been built. They therefore represent the lower part of the filling of the old volcanic pipe or conduit, and those that are exposed belong to the older volcanoes of the

world. The presence of the solid lava plug is of course inferred in all uneroded volcanoes, and indeed it is a necessary part of an extinct example. The part it takes in the determination of a volcano-like hill as an extinct volcano is illustrated by the classical case of the Kammerbühl, a small hill in northern Bohemia, which played a leading rôle in the days when geologists still discussed the question of the origin of beds of basalt,— one group, the followers of Werner, holding that this rock was precipitated from water, while another group argued for its volcanic origin.

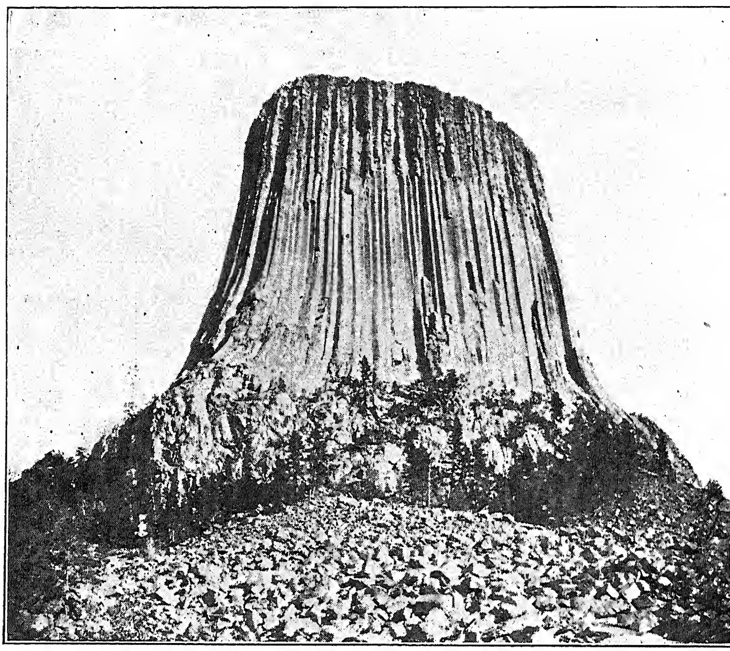


FIG. 111. — Mato Tepee, Devil's Tower, Wyoming, a supposed volcanic neck showing vertical columnar structure. (Photo by N. H. Darton, U. S. G. S.)

The hill in question (Fig. 112 *a*) is composed mainly of cinders and altered sediments, with a small basalt stream on one side. Werner and his followers contended that the material of this hill and others like it was formed by the combustion of beds of coal, which had not only burned the older slates and the younger rock material, but had also in part melted a layer of basalt of aqueous origin, and so produced the cinders. The poet Goethe, however, believed

this hill to be an extinct volcano, and argued that if a tunnel were driven into it the hardened plug of lava in the old pipe would be encountered near its center. To prove the correctness of the view of the poet-naturalist, his friend Count Caspar von Sternberg had the tunnel driven in 1837, with the result that the volcanic plug was found and its connection with the basalt layer proved (Fig. 112 *b*). This virtually ended the controversy about the origin of basalt.

FIG. 112 *a*. — The Kammerbühl, an old volcanic hill in Bohemia.

Sometimes old lava plugs may be modeled out in relief by the erosion of the older sediments which were penetrated by the volcanic pipe. In such a case the resulting hill is essentially a neck, not readily distinguishable, except perhaps in the material of which it consists, from necks produced by the removal of the volcanic cone only. An example of such an older neck is found in Edinburgh, Scotland, where it forms the famous peak known as Arthur's Seat, near Holyrood Castle. The material of this peak consists of hardened basaltic lava and fragmental rock in which not infrequently are found pieces of wood from the trees which clothed the slopes of the ancient volcano. These wood fragments, now silicified, were buried in the fragmental material which filled the old throat of the volcano, and which probably extends to some depth because of the sinking of the old lava plug on solidifying.

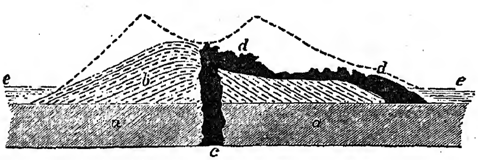


FIG. 112 *b*. — Section of the Kammerbühl, showing the probable former outline of the volcano and the old volcanic plug. *a*, metamorphic rocks; *b*, basaltic scoriæ; *c*, plug of basalt; *d*, stream of basalt; *e*, alluvial beds..

Sections of volcanic plugs in the older rocks are often exposed by erosion. An illustration of one such from the coast of Ireland

is here given in Fig. 113 *a*, and a second, still joined to the basaltic lava sheet, in Fig. 113 *b*. The basaltic lava penetrates the chalk, which was altered to marble by the heat of the basalt. It is probable that these are not the plugs filling the pipes of separate volcanoes, but that they represent fissures through which lava reached the surface in the form of a great sheet, as described later. A similar plug may be seen on the Nova Scotia coast at Wasson's Bluff, not far from Parrsborough. Here the volcanic material penetrates old sandstones and gypsum beds of late Palæozoic age, and belongs to the eruptions of Triassic time which produced the great lava sheet of Cape Blomidon and adjoining regions.

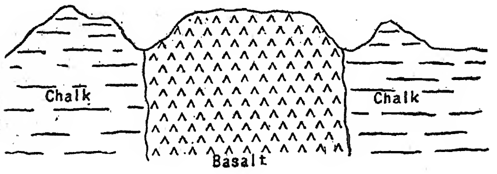


FIG. 113 *a*.— Section of volcanic plug (basalt) in chalk. Coast of Antrim, Ireland. (After Geikie.)

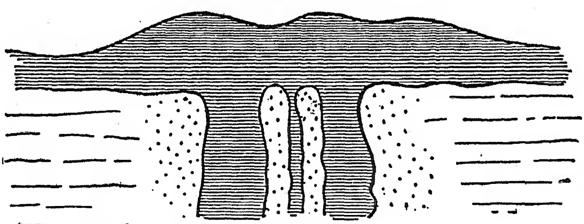


FIG. 113 *b*.— Marmorization of chalk beds by basalt. Island of Rathlin on coast of Antrim, Ireland. (Leonard.) The marble is dotted. (From Kayser's *Lehrbuch*.)

Sections of old volcanic plugs are abundant in some districts. Thus on the famous shore of County Fife in Scotland, no fewer than eighty are found in a space twelve miles in length by from six to eight in width. These plugs (Fig. 114) penetrate sandstones, shales, limestones, and coal beds, and are consequently of more recent date than the periods during which these sediments were deposited (Mississip-

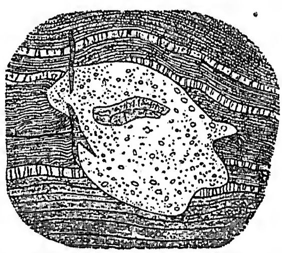


FIG. 114.— Ground-plan section of the plug of an old volcano on the shore of St. Monans, Fife, Scotland. (After Geikie.)

pian, see Chapter XXXVI). The sections of the plugs are roughly circular or elliptical, varying in size, and from them dikes and sheets of igneous material not infrequently penetrate the adjoining rocks, after the manner of the radiating dikes seen in modern volcanoes, as already described. The plugs of Fife are not placed along lines of great fissures, as might be supposed, but penetrate the rocks apparently without any relationship to its structure. That necks are, however, ranged along great lines of fissures in the earth's crust is frequently found, and is seen in the alignment of some of the necks of the Auvergne region in France (see *ante*) and elsewhere, and may be inferred from the arrangement of the volcanoes of Iceland. Here the lava first welled up through a recognizable fissure in the earth's crust, which subsequently was partly closed by the hardening of the lava, so that only the broader portions remained open. These were converted into volcanic pipes, above which individual volcanoes were built up (Fig. 115). The Japanese volcanoes, too, seem to be arranged along great lines of fissures, and this is probably true for the majority of existing volcanoes, as is indicated by their linear arrangement (Fig. 116).

The material filling the volcanic vents, and therefore the material of necks and plugs, ranges from basalt to rhyolite, according to the acidity of the volcanic mass. When deeper portions of the necks are exposed they show rocks of coarser crystalline type, even gabbro and granophyre, which have resulted from slow cooling. In other cases fragmental ma-

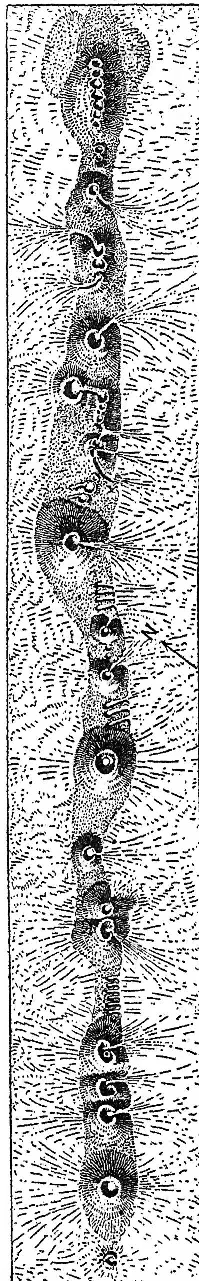


Fig. 115. — Map of the volcanoes built up over a fissure in Iceland. (After Suess.)

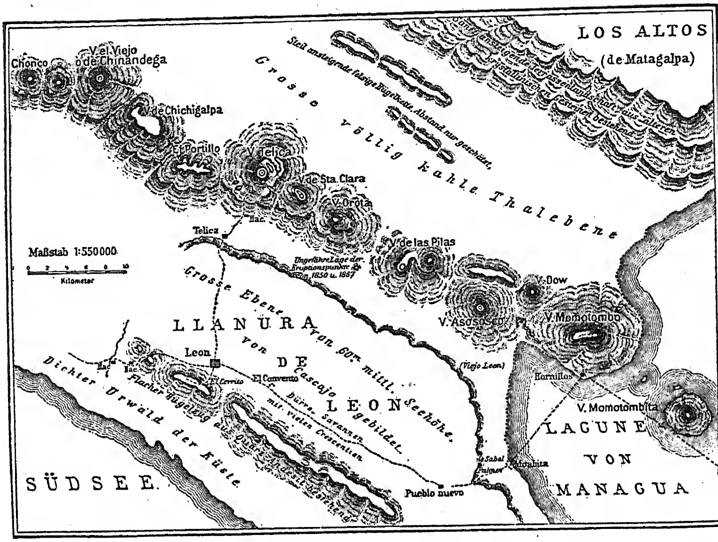


FIG. 116. — Volcanoes in Nicaragua, showing linear arrangement apparently along a fissure line. This line is parallel to the trend of the mountains and ridges, and to the coast line. (After Karl von Seebach, from F. Ratzel, *Die Erde.*)

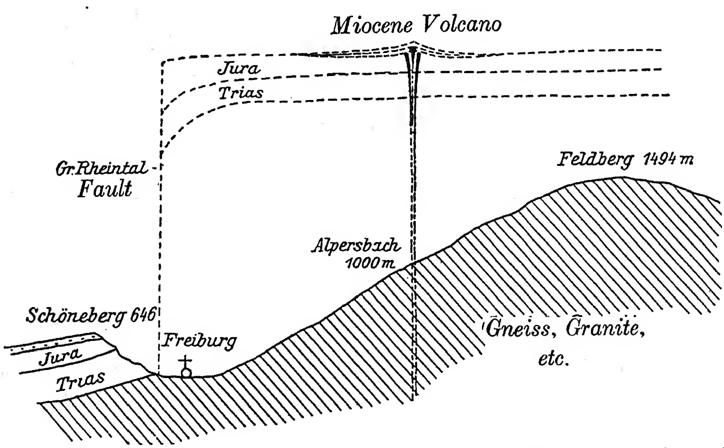


FIG. 117. — Diagrammatic section through the Freiburg region (i. Br.) showing the former and present topography and the extensive erosion. (After Th. Lorenz, from Kayser's *Lehrbuch.*)

terial (agglomerate and tuff) fills the ancient vent, as in the case of the Nova Scotia plug already cited. A mixture of both may occur, and the structure may show evidence of successive eruptions through the same vent, and the formation of a cylinder of lava within a cylinder. Finally, as already noted, the lava may enclose fragments of the wall rock, generally from a deeper horizon. The relationship of a plug to the old volcano in a much-eroded region is shown in the section on the preceding page (Fig. 117).

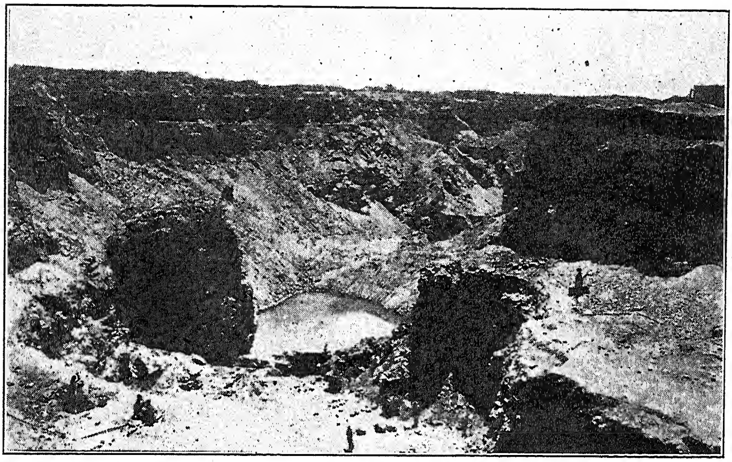


FIG. 118. — Diamond mine in old volcanic plug, South Africa.

In South Africa, old volcanic plugs have become of great economic importance, for it is in them that the great diamond mines are located. These plugs, which are often of funnel form, broadening upward in diameter to 300 and in exceptional cases to 685 meters, are composed of brecciated rock, the so-called "blue ground" which contains the gems (Fig. 118). Whether the diamonds represent the crystallized carbon of wood included in the plugs as in those of Scotland, or whether the carbon is of subterranean origin, is an open question. The character of the diamond-bearing material suggests that it may have risen from great depths.

Sheet Lavas Formed by Fissure Eruption

Not all lava reaches the surface through volcanic pipes above which volcanoes are built. Indeed, we have seen that some of these pipes, as in the Icelandic volcanoes, are merely the reduced expression of large fissures which opened in the earth and through which the lava at first reached the surface, after which volcanoes were built up on those spots where the fissure became broken up into disconnected pipes. In some of the grandest eruptions of molten rock, — generally basalt, — no volcanoes are built up, or at least not until long after the eruption begins. Instead, great flat surfaces of lava

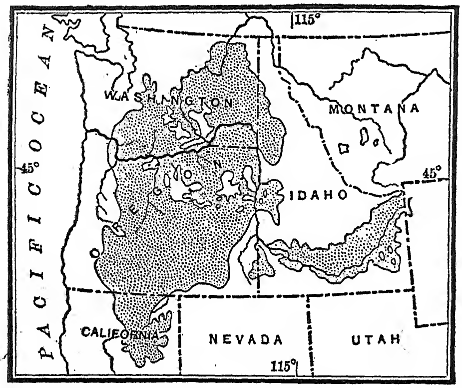


Fig. 119 *a*. — Map of the Columbia and Snake River lava fields. (After Bowman.)

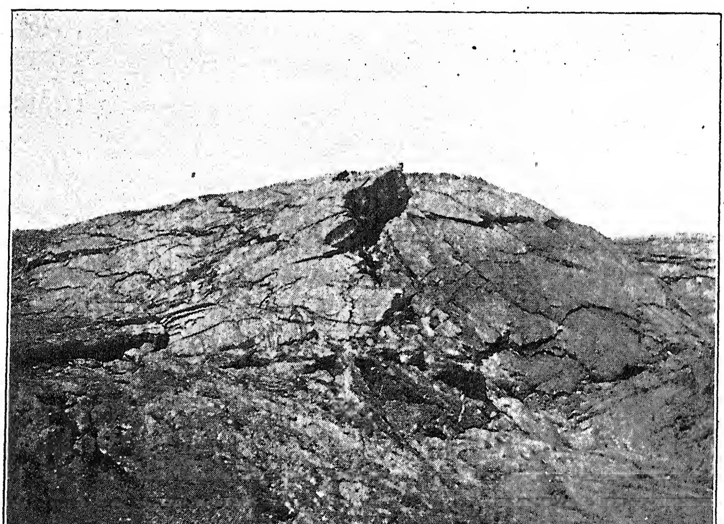


Fig. 119 *b*. — "Gordon Craters," Malheur County, S. E. Oregon. Irregularities in surface of recent lava, produced by pressure. (Photo by Russell, U. S. G. S. Courtesy of D. W. Johnson.)

— lava plains or plateaus — are produced. Fissure eruption, in which the lava wells up along the entire length of the fissure, is seen to-day in Iceland. Along the great Eld Cleft, lava has welled up in historic times, spreading on both sides of the fissure to form a flat basalt plain, 270 square miles in extent. Along the southern prolongation of the fissure, however, where it was narrower, a row of low cones has been formed, through isolation of a series of vents.

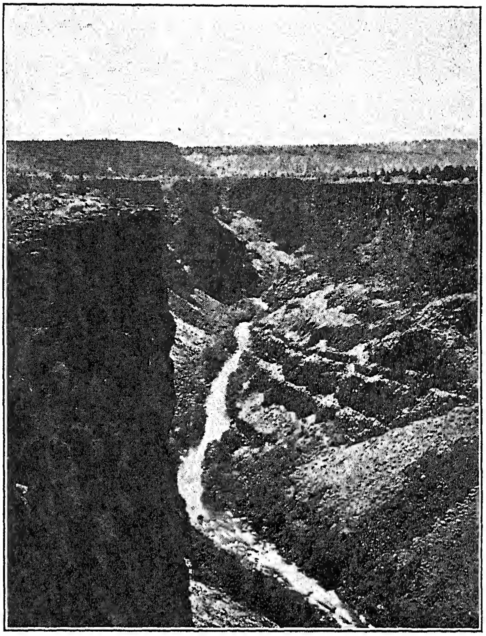


Fig. 119 *c*. — Cañon in the lava of the Snake River plateau.

One of the largest lava plains of this type is the Columbia and Snake River plain, which covers an area of 200,000 to 250,000 square miles in Washington, Oregon, Idaho, and California (Fig. 119 *a*). The lava apparently spread over a region of varying topography, filling the valleys and burying the smaller hills, surrounding the larger ones, and penetrating the valleys in their sides. A succession of outpourings occurred, sometimes at short intervals, sometimes long enough apart for the production, by weathering, of old soil beds upon the preceding sheets, which were occasionally covered with forests before the next lava sheet was poured out. The present surface of this lava plain is in many places barren and desolate beyond description, but in some places low cones rise above it, formed probably during the later stages of volcanic activity, or the surface is broken by pressure (Fig. 119 *b*). Where cañons are cut by rivers, the nature of the material is well shown (Fig. 119 *c*).

Another extensive flat lava plain formed by fissure eruption

covers Central India, and forms what is known as the Dekkan Plateau. This has a present area of some 200,000 square miles, but probably was originally much larger. The thickness of the basalt sheet, generally spoken of as the Dekkan Trap, is in places more than a mile. No cones have been built upon its surface.

Remnants of an equally extensive lava sheet of this type are found in western Europe, where they occur on the west coast of Ireland (Giant's Causeway, etc.), Scotland, Staffa, the Orkney and Faroe Islands, and perhaps Iceland. The active work of the sea, aided no doubt by the weather, has removed large parts of this plateau,

FIG. 120. — Basaltic columns of the Giant's Causeway, on the coast of Ireland.

while others have probably subsided beneath the sea-level by recent disturbances of that part of the earth's crust. This lava sheet, too, is composite, and beds with plant remains, from which the age of the eruption can be ascertained, lie between successive flows.

Remnants of much older (Triassic or Jurassic) lava flows probably of this type are found in New Jersey (Watchung Mountains), in the Connecticut Valley of Connecticut and Massachusetts, and along the shores of the Bay of Fundy in Nova Scotia. In New Jersey and elsewhere the peculiar character of the base of the sheet sometimes indicates that the lava overflowed bodies of

standing water, with the result that steam pipes and a comminuted basal structure were produced, the mud from the bottom of the lake or pond being forced up into the lava. In cavities thus produced many famous mineral deposits (zeolites, etc.) were subsequently formed. This structure is also found in lava sheets of basic volcanoes.

A characteristic feature of many of these basaltic sheets is the development of prismatic columns, which generally stand vertical,

FIG. 121. — Near view of a portion of the columnar basalt of the Giant's Causeway, coast of Ireland. The upper surfaces of the transverse joints are seen to be convex in most of the columns, but in a few cases they are concave, holding small pools of water.

as so finely shown in the Giant's Causeway on the north coast of Ireland (Figs. 120, 121). Sometimes, however, these columns are curved, as is seen in some parts of the island of Staffa off the Scottish coast, while in other parts they are vertical as at the entrance to Fingal's Cave (Figs. 122 *a–d*). This columnar or basaltic jointing is also seen in some of the basalt sheets of the Columbia lava plateau and the basalt of the Watchung Mountains, and is indeed a fairly common structure in basaltic lavas. The name *joint* is unfortunate, as these structures have little in common with the true joints, which are fractures in the earth's crust, and of

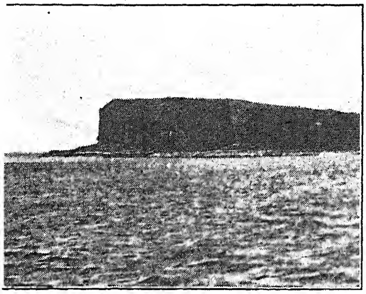


FIG. 122 *a*. — General view of the Island of Staffa from the sea. Note the columnar basalt capped by massive basalt. Entrance to Fingal's Cave near the center of the view. (Photo by author.)

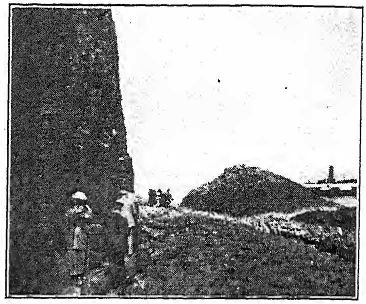


FIG. 122 *b*. — The island of Staffa, showing the basalt columns capped by massive basalt on the left and an eroded surface of basalt columns on the right. Curved columns in the distance. (Photo by author.)

FIG. 122 *c*. — Fingal's Cave on the island of Staffa, showing the columnar jointing. This is a sea-cave, eroded by the waves which remove the columns. The floor of the cave is covered by sea-water even at low tide, though a narrow path has been constructed on one side. The roof of the cave is formed by the non-columnar capping-mass of basalt, as is shown in Fig. 122 *d*. (See further: Chapter XXIII, and Figs. 720, 721.) (Photo by author.)

secondary origin. The columnar structure, on the other hand, is a primary structure, and is caused by a radial contraction of the

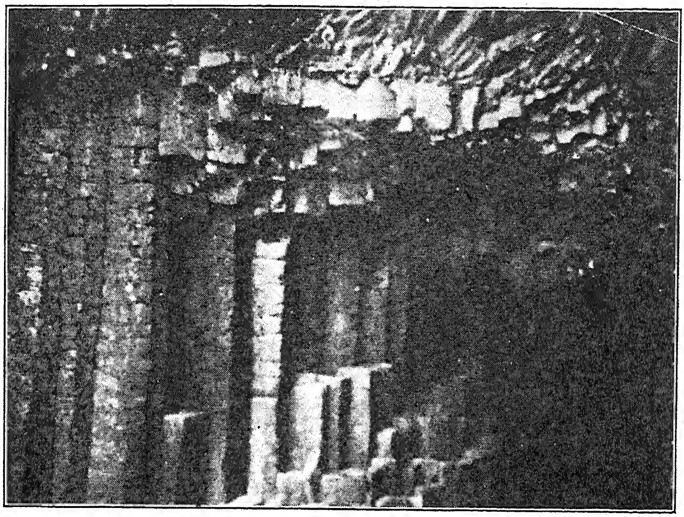


FIG. 122 *d*. — Wall and roof of Fingal's Cave, Staffa, showing the cross-jointing of the columnar basalt, and the irregular appearance of the massive basalt which forms the roof of the cave. (Photo by author.)

cooling lava mass about a series of equally spaced centers (Fig. 123). As a result six-sided prisms are produced. A characteristic feature of these prisms is the curved form of the horizontal or transverse

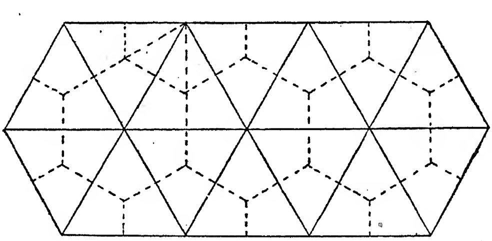


FIG. 123. — Diagram illustrating the formation of contraction prisms. The centers of attraction are connected by solid lines. The prisms formed are dotted. (From Grabau, *Principles of Stratigraphy*.)

planes, which generally separate them into component blocks (Figs. 121, 122 *d*). Prismatic structure, though best developed in basalt, is not confined to this rock, but occurs even in such acid lavas as obsidian (Fig. 124). The position of the columns is, in

general, at right angles to the surface of the mass in which they are developed, while diverging and curved columns are often developed just below the surface of the lava sheet. Examples of

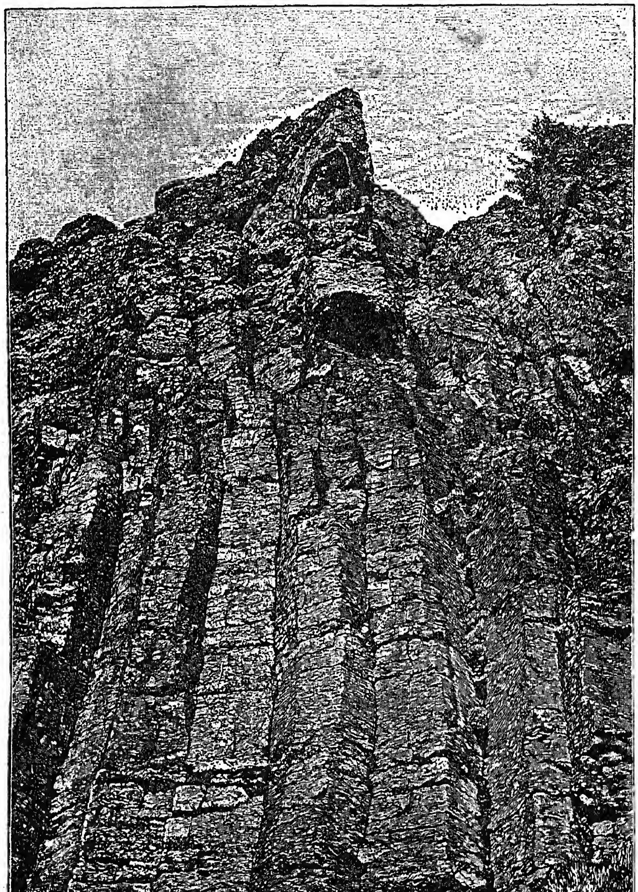


FIG. 124.—Columnar jointing in obsidian, Obsidian Cliff, Yellowstone National Park. (U. S. G. S.)

such curved columns are seen, as before noted, in parts of the island of Staffa and in parts of the basalt sheets of the Watchung Mountains, New Jersey.

Minor Phenomena Generally Associated with Closing Stages of Volcanicity

There are a number of igneous phenomena which are manifested upon the surface of the earth to-day, which are regarded as primarily associated with the dying stages of volcanicity. These may be enumerated in the order of their importance as follows:

a. Solfataric action.
b. Fumarolic activity.
c. Mofettes and effervescent springs.
d. Mud-volcanoes.
e. Geysers.
f. Hot springs.

Fig. 125.—The Solfatara at Pozzuoli, Italy. The steam and gases issue in one corner of the nearly extinct volcano.

Solfataric action.—The volcano of Solfatara (Fig. 125), in the Phlegræan fields near Naples, represents a dying stage in volcanicity, giving off steam and gases only, since its last eruption in 1198. The crater of Solfatara is very wide, but its walls are only about 100 feet high, while its floor is marshy and salt-encrusted, with occasional pools of boiling water. On one side, at the foot of the crater wall, a jet of steam escapes from an opening and rises to a height of 6 or 7 yards. In Iceland, Java, New Zealand, the Andes, and elsewhere, such *solfataric vents*, as they are called, are common, indicating the dying condition of those particular volcanoes. Besides the steam many other gases are given off, these including hydrochloric acid gas, sulphur dioxide, sulphureted hydrogen, ammonium chloride, and, in the case of the Italian *Saffioni*, boracic acid, which forms the source of the important borax industry of Tuscany.

Fumaroles. — These are typically emanations of steam, from fissures, or from cooling lava surfaces, but they also vary, especially with the decrease in temperature of the lava or other source. Above 350° C. only dry fumaroles exist, these giving off chiefly anhydrous chlorides. Between this and a temperature of 100° C. fall the acid fumaroles, which give off hydrochloric acid and sulphur dioxide, with some steam. At about 100° C. occur the alkaline fumaroles, which give off steam and ammonium chloride, and

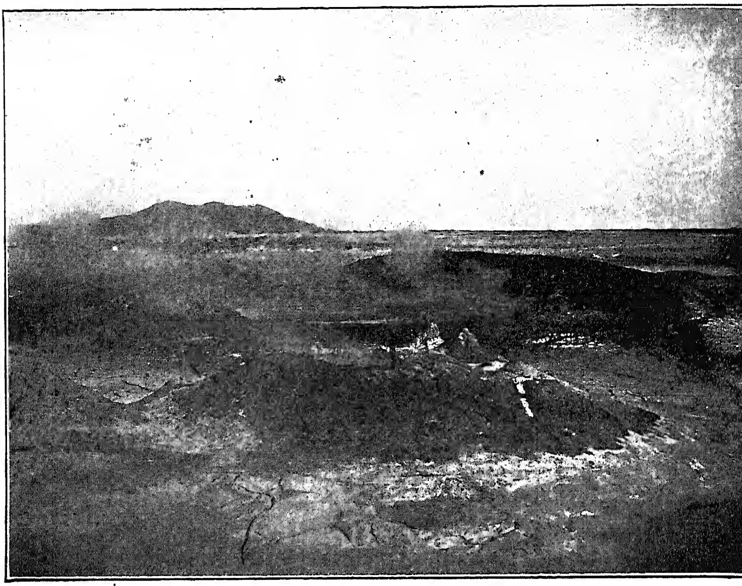


Fig. 126. — Active mud-volcanoes near Volcano Lake, Cerro Prieto, Delta of the Rio Colorado. The largest of the group, seen in the distance, is now quiescent. (Courtesy of the American Geographical Society, Broadway at 157 St., New York. From the *Geographical Review*.) (For location, see map, Fig. 166.)

below 100° C. fall the cold fumaroles with nearly pure steam. The famous valley of Ten Thousand Smokes, in the Katmai Peninsula of Alaska, is a prominent example of fumarolic action on a large scale.

Mofettes. — These give off only carbon dioxide, nitrogen, and oxygen at the temperature of the atmosphere. Caves in which such gases are given off exist in many volcanic districts; and they are sometimes exhibited to tourists with the lowering into them of dogs or other luckless animals, which quickly become unconscious,

after which they are drawn up and revived. The carbon dioxide, on account of its weight, remains near the bottom of the cave. Effervescent springs, *i.e.* water charged with CO_2, occur in many old volcanic regions.

Mud-Volcanoes. — Among the subordinate phenomena associated with or comparable to igneous activities, is the formation of mud-volcanoes (Fig. 126). These are cones built up of mud with small craters at the summit, resembling miniature volcanoes. Their height varies from a few feet to a hundred feet or more,

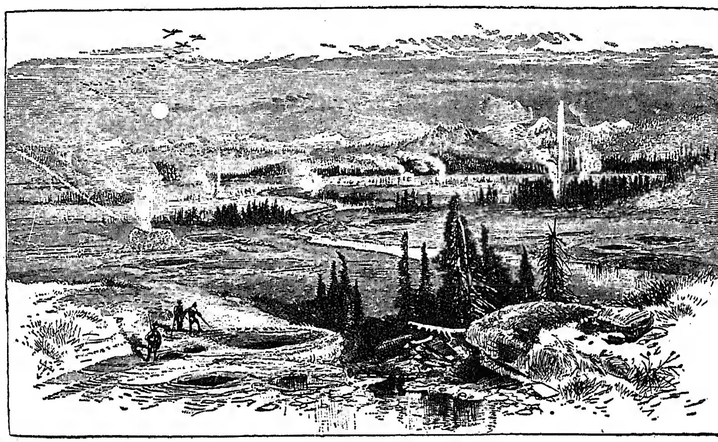


FIG. 127. — The Great Geyser Basin of the Madison River in Yellowstone National Park. (Guyot.)

and their activity is either constant or intermittent, quiet or explosive. They are formed by highly heated steam or by gases, which rise through a superficial layer of mud and originate from underlying lava beds or from chemical reaction. The mud is built up into cones of the volcanic type. As the material is soft, however, these cones are readily destroyed by rains, etc.

Examples are known from the Colorado Desert, from lower California, the Yellowstone Park (the Paint Pots) and elsewhere in this country. They also occur at Baku on the Caspian Sea and in the Crimea, where some of them rise to 250 feet in height, and are provided with apical craters.

Geysers and Hot Springs. — Geysers are springs of hot water which erupt violently at intervals, with periods of quiescence between. They have essentially the same relation to ordinary hot

springs that volcanoes of intermittent explosive eruptions have to those of quiet and constant lava flows. Geysers are abundant in Iceland, in New Zealand, and in the Yellowstone Park, where there are about 100 active examples and more than 3000 hot springs (Fig. 127). A geyser consists typically of a more or less circular basin surrounded by a rim of silicious material (geyserite), and this commonly forms the upper part of a cone comparable to a volcanic cone and its crater. From the center of the basin a pipe of circular section and with smooth wall descends, this and the basin being filled with water. In the typical Great Geyser of Iceland, the cone is about 120 feet in diameter and 13 feet high, while the crater-like basin at the top is 60 feet in diameter and 5 feet deep. The central tube or pipe has a diameter of about 10 feet, with smooth, cylindrical, vertical walls. The temperature of the water which fills the pipe and basin ranges from 75° to 90° C., but at a depth of 70 feet in the pipe the temperature is about 130° C. The eruption occurs at almost twenty-four hour intervals, and the water of the basin is thrown to a height of nearly 100 feet. The characters of the other geysers are similar, though differing in detail. The appearance of the Giant Geyser of the Yellowstone is shown in Fig. 128, and of Old Faithful in Fig. 129. Diagrammatic sections of the two main Icelandic examples, "The Geyser" and "Strokr," are given in Fig. 130.

FIG. 128. — Giant Geyser of the Yellowstone. (After Hayden.) The eruptions of this geyser occur at intervals of 7 to 12 days, and last for full 60 minutes at each eruption. The column is thrown to heights of 200 to 250 feet.

The eruption is due to the heating, above the boiling point, of the water at a depth, while at the same time the pressure of the column

of water keeps it from changing to steam. With increased heating, however, the point is reached where the water will change to steam in spite of the pressure, and the expansion of the steam raises the

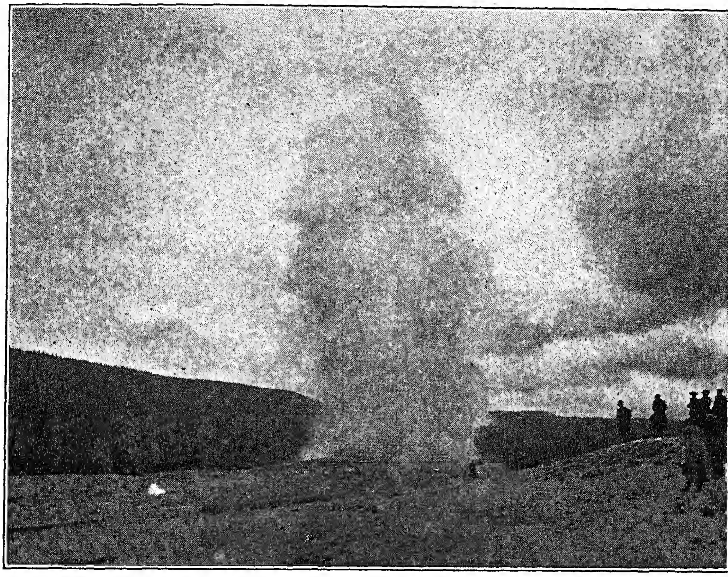


FIG. 129. — Old Faithful Geyser in eruption, Yellowstone National Park. (Photo by D. W. Johnson.) The eruptions of this geyser occur at intervals of 60 to 75 minutes, each eruption lasting 4 minutes. The height to which the column is thrown is 125 to 150 feet. The eruptions are heralded by loud rumblings, with spasmodic outbursts of jets 10 to 20 feet in height, then the column is suddenly thrown up with a loud roar, maintaining a height varying from 90 to 150 feet for two or three minutes with occasional steeple-shaped jets rising still higher, the jets varying, and giving off great rolling clouds of steam; then the jets gradually decrease in altitude, and in five minutes the eruption is over, the tube apparently empty but emitting occasional puffs of steam for a few minutes longer. During the eruption the water falls in heavy masses about the vent, filling the basins surrounding it and running off in all directions. The estimated discharge is 3000 barrels at each eruption.

column of water, and so lowers the pressure, with the result that a large amount of steam is suddenly formed from the super-heated water, and the eruption takes place. The source of the water is believed by some to be the ground-water, and by others it is regarded as new or juvenile water, given off by subterranean igneous masses in the process of cooling. The heat is probably in all cases of volcanic origin. The geysers of Iceland and New Zealand are situated in regions of still active volcanicity, while those of the

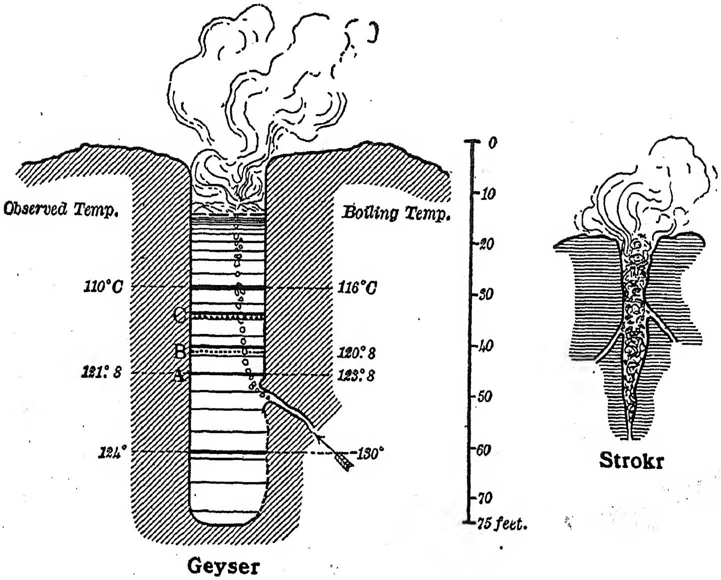


FIG. 130. — Semidiagrammatic sections of the Icelandic geysers, "The Geyser" (the type) and "Strokr." Strokr has a funnel-like pit 36 feet deep and 8 feet across, expanding into a saucer-like basin. The tube is generally filled to within 6 feet of the top with clear water, which boils furiously, owing to the escape of great bubbles of steam coming from two openings in opposite sides of the tube. When the eruption took place, the jets rose in a sheaf-like column to a height of 100 or more feet. Eruptions took place at very irregular and long intervals; but they could be produced in a short time by "putting a lid on the great kettle," by dumping in large pieces of turf. "The Geyser" is a pool of limpid green water, whose surface rises and falls in rhythmic pulsations. The usual temperature is 170° F. (76.6° C.) or 200° F. (93.3° C.) but varies, being greater immediately before eruption. The shallow saucer-like basin is about 60 feet across and slopes gently to a cylindrical shaft 10 feet in diameter, forming the pipe of the geyser; this being about 70 feet deep. The tube is very regular. Before an eruption, bubbles of steam entering the tube suddenly collapse with loud but muffled reports and a disturbance of the quiet surface of the water. During this "simmering," the water rises in dome-like mounds over the pipe and overflows the basin, running down the terraced slope and wetting the cauliflower-like forms of sinter that adorn it. Domes of water rise in quick succession, and finally burst into play, followed by a rapid succession of jets increasing in height until the column is 90 to 100 feet high, accompanied by dense clouds of steam. This lasts a few moments and then ceases, and the basin is empty and apparently lined with a smooth coating of white silica. The great geysers of the Yellowstone surpass this in magnitude of eruption, but not in beauty. (Weed.)

Yellowstone are in a region where volcanoes have recently become extinct.

The hot waters commonly carry silica is solution, and this is deposited partly by the cooling and partly by the aid of low organisms, especially algæ, and so the cone of silicious sinter is built up (Fig. 131). The quiet flowing hot springs more commonly deposit carbonate of lime. These deposits will be discussed in a subsequent chapter.

Geysers are commonly affected by earthquakes which disturb the arrangement of the rocks of the region. The Icelandic geyser

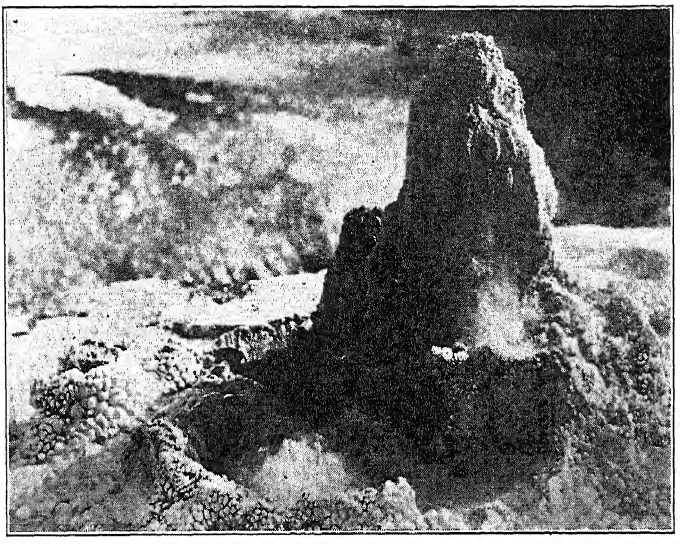


Fig. 131. — Spike Geyser, Witch Creek, Yellowstone Park. Showing an exceptionally fine mass of silicious sinter (geyserite) built up around the basin. The sinter shows botryoidal surfaces. (Photo J. P. Iddings, from U. S. G. S.)

Strokr is said to have come into existence during the earthquake of 1789, and the earthquake of 1896 put an end to its activity. It has not been in eruption since. A new geyser or hot spring appeared after the shocks of the first day (Sept. 15) of the earthquake of 1896, this spring throwing water and rocks to an estimated height of 600 feet, but in a few hours it subsided to a height of 10 or 12 feet. It ceased to flow altogether after ten days.

CHAPTER IX

FORM AND STRUCTURE OF OLDER IGNEOUS MASSES

Types of Older Igneous Masses

Leaving now modern volcanoes and those which have so recently become extinct that their characteristics can still be readily recognized even though modified by erosion, we must next turn our attention to those rock masses and structures of igneous origin which were formed at a depth in the earth's crust, and have become visible only as the result of erosion of the overlying rocks, or through dislocation of the earth's crust. These may be grouped under the following divisions: 1. Dikes; 2. Stocks; 3. Sills; 4. Laccoliths and related types; 5. Bysmaliths; 6. Bosses; 7. Batholiths.

The first five groups are classed as intrusive or *hypabyssal* masses, to which group the volcanic plugs may also be referred, especially that part which penetrates the older rocks beneath the volcano. Bosses and batholiths are classed as deep-seated or *abyssal* igneous rocks, and they may in general be regarded as representing the hardened pools of igneous material from which both the intrusive and the extrusive or volcanic masses are derived.

Intrusive or Hypabyssal Igneous Masses

Dikes. — In modern volcanoes, as we have seen, the eruption does not always take place through the crater, but a fissure may open in the mountain side through which the lava wells out, and upon it there are generally built up subsidiary or parasitic cones or series of cones, the so-called *monticules*. This fissuring of the mountain side is due to the fact that the material of the mountain, which is often in large part volcanic ash only, is shattered with comparative ease by the pressure of the rising lava, while the hardened plug of lava, which fills the throat of the crater, cannot be lifted except by a much greater force.

When lava hardens in the fissures formed in the sides of the volcano, a dike is produced. This is so called, because erosion often removes the soft tuffs and other material, leaving the hardened lava mass projecting as a wall. Fine examples of such dikes cutting stratified tuffs are seen on the flanks of the Sicilian volcano Etna, especially in the Val-del-Bove, as already noted (Fig. 79, p. 134).

Such dikes are also found in many districts of recently extinct volcanoes, but they are not confined to the cones of volcanoes. In-

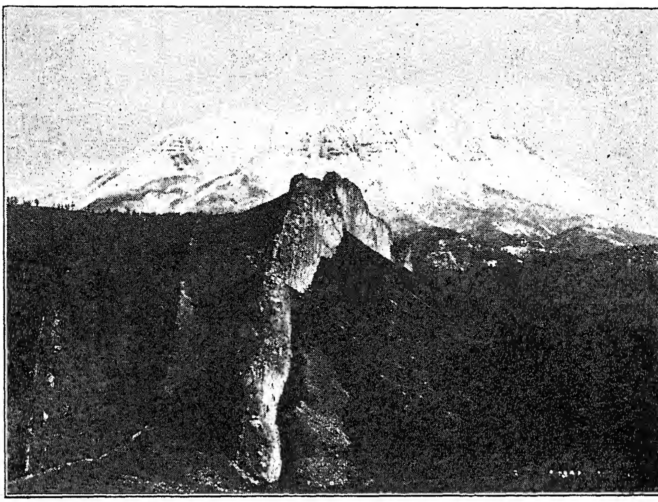


Fig. 132. — West Spanish Peak, Colorado, from the northwest. In the foreground, a large dike and several small dikes weathered-out in relief. (After Stose, from U. S. G. S.) (See map, Fig. 138, p. 195.)

deed, where eruption takes place through fissures in the earth, without the building of volcanoes, the hardening of the lava in the fissure produces a dike. As, in such cases, the country rock is often much older, the contrast which the dikes form with it is generally very marked. Of course, such dikes will not become visible until the lava sheet of which they formed the vents is removed, or until a marginal section is cut into the igneous mass by the sea or other agent with the consequent uncovering of the dike.

Over much of western North America the great lava sheets are still in place, and the dikes which connect with them are not visible. Over much of Great Britain, however, the basalt sheet of similar age, and which probably extended to Iceland, has been removed by

erosion, in part by the sea, and in part by atmospheric agencies. As a result, the manifold types of rocks which make up the British Isles are found transected by numerous dikes of basaltic material, most of which have no apparent relation to any existing masses of solidified lava. Some of these have been traced for a distance of 60 or even 90 miles. Dikes connecting with remnants of the basaltic sheets are also exposed on the seashore. In some cases the dikes, being more resistant than the enclosing rock, have with-

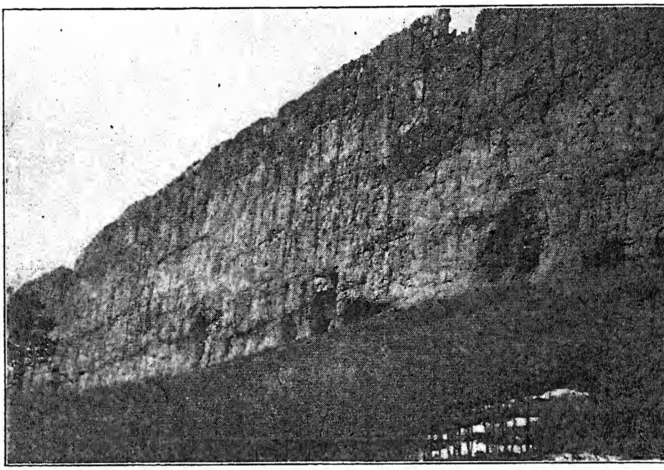


FIG. 133. — View of the great dike, running north from West Spanish Peak, Colorado. This dike originally cut nearly horizontal strata which have weathered away, leaving a continuous wall 100 feet high. The horizontal markings along the side of the wall indicate the original contact with the stratified rocks. (Stose, photo; from U. S. G. S.)

stood erosion, while the country rock has been worn away. As a result, they stand above the country like stone walls, a fact which first gave rise to the name dike, since they are not unlike the artificial dikes built in some portions of western Europe, especially the Netherlands, to keep out the sea from the low-lying lands (Figs. 132–134).

Along the border of the great trap sheet which forms the Dekkan Plateau of Central India, where the sea or other agents have eaten away a part of the outer margin of the sheet, dikes are not infrequently exposed, penetrating the basement rock upon which the trap sheet lies. For the most part, however, the dikes cannot be traced directly to the trap, though the connection is indicated by the

similarity of the material. Dikes of probably much older origin are found abundantly along the Massachusetts coast, and to a lesser extent along the Maine coast and elsewhere. Here they generally consist of the type of basalt known as *diabase* (see p. 106), a lava which has cooled with sufficient slowness to permit the development of recognizable crystals. We must, therefore, conclude that these dikes represent the deeper portions of fissures filled by lava, where, on account of the depth below the surface at that time, the cooling was slow. Often a columnar structure is found in these

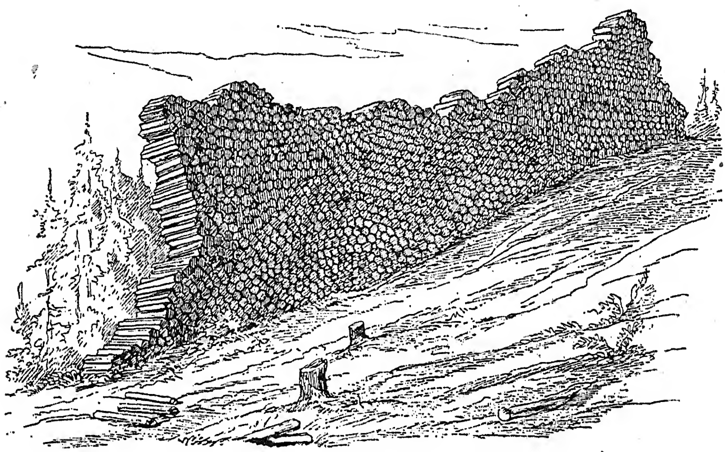


Fig. 134. — Devil's Wall (*Teufelsmauer*) near Oschitz, Bohemia. A basaltic dike, 25 km. long, 2 meters thick — with horizontal prismatic joints. Weathered in relief, wall-like. (From Kayser's *Lehrbuch.*)

dikes, the columns extending across them from wall to wall (Fig. 134). Where the sea has access to them after they have become exposed on the surface from the erosion of large masses of rock, these columns are frequently removed by the waves, leaving a deep, parallel-sided fissure, into which the sea penetrates with great force during storms and at high tide. Sometimes caverns are formed by the removal of the lower columns only; when the compression of the air in these caverns under the impact of the wave will result in producing a regular series of water spouts after each inrush of the waters. Such phenomena are common on dike-infested coasts and are known as "spouting horns," etc. Chasms left by the removal of dikes are characteristic features of the rock-bound New England coast (Fig. 135). Many other igneous rocks

besides basalt and diabase occur in the form of dikes, and it may be inferred that a majority of them never reached the surface as molten lava but cooled in blind fissures of the earth's crust. Their present exposure is therefore brought about by removal, through erosion, of the rock which once concealed them. Among the more frequent occurrences are those of granite (aplite, etc.), and especially of the coarse or giant granite, *pegmatite* (Fig. 136). These pegmatite dikes are often of great width, and form the source of many rare mineral deposits, besides yielding feldspar, quartz, and mica in sufficiently large masses to be commercially valuable. In some cases dikes of this and other kinds have branches, and sometimes they are extremely irregular, having perhaps eaten their way into the country rock. Such irregular dikes are also spoken of as igneous veins, though they have little in common with true veins (see p. 265).

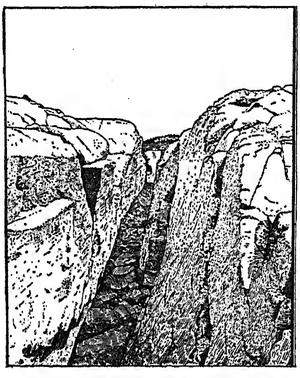


Fig. 135. — An eroded diabase dike in granite; west side Rockport Point, Cape Ann, Mass. In the bottom of the chasm the dike is seen covered by boulders which were formed by the waves from the dike material. At present the chasm is above high-water mark, showing recent elevation of the coast. (After Shaler, U. S. G. S.)

The essential character of dikes may be summed up by saying that they are generally of considerable lineal extent, continuing sometimes for many miles, and of uniform width, ranging from a fraction of an inch to many feet. When they cut bedded strata, they may do so at any angle, but in general, dikes have an approximately vertical position, though this may be changed by subsequent movements of the entire mass. Around old volcanic centers dikes are often radially arranged, as shown on the island of Mull, west coast of Scotland (Fig. 137), and in the ancient volcanic center of the Spanish Peaks in Colorado (Fig. 138), the dikes of which have already been referred to (Figs. 132, 133). Frequently dikes of different ages intersect one another, in which case the younger can be recognized by the fact that it cuts the older. In the broader dikes the rock texture of the marginal portion is commonly finer than that of the center, because more rapid cooling took place where the igneous rock was in contact with the cool country rock which it

penetrated. This is especially well recognized in the case of the dike rocks of coarser grain. Sometimes the marginal texture is even glassy, and the color and composition may also vary from the margin to the center. The wall rock of dikes and the basement rock of lava flows frequently show a certain amount of alteration due to the heat of the lava mass. This *contact metamorphism* (see p. 207) is seldom very extensive, however, dying out a short distance from the igneous mass, especially when this cooled rapidly near the surface. Lava streams have indeed been known to flow over ice masses without completely melting them. This argues

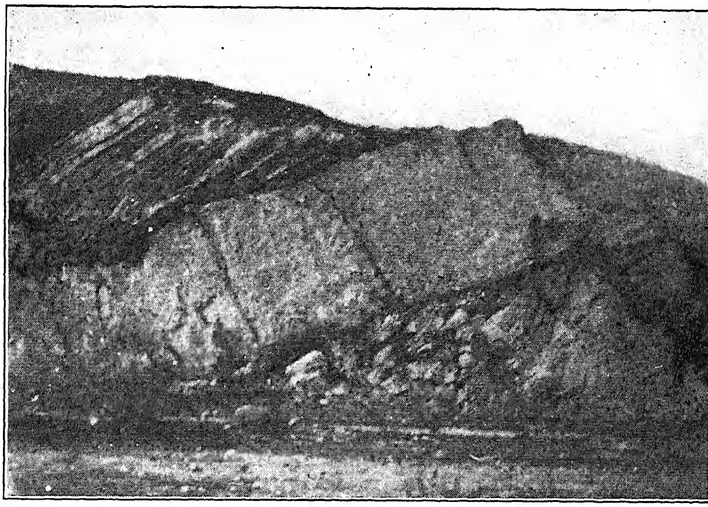


Fig. 136. — Pegmatite dike in crystalline dolomite, New York City.

for a comparatively rapid cooling of the lava exposed on the surface of the earth.

Stocks. — These are dike-like intrusions which are of short extent, sometimes more or less regular and cylindrical, at others irregular. They are similar to volcanic plugs or cores, such as fill the conduits of old volcanic pipes, but differ from them in not reaching the surface, though the name has been indifferently used for the intrusions of plug-like character of moderate size, even those that are in reality the filling of ancient volcanic conduits. It is true that it is not always possible to determine in any particular case whether the intrusion reached the surface and formed a volcano, or whether it extended only part way up into the rocks of the

earth's crusts. In such a case the name stock is best applied to these structures. In character they partake of the deeper portions of volcanic plugs or pipe fillings, and to some extent of those of dikes as well, especially if they are irregular.

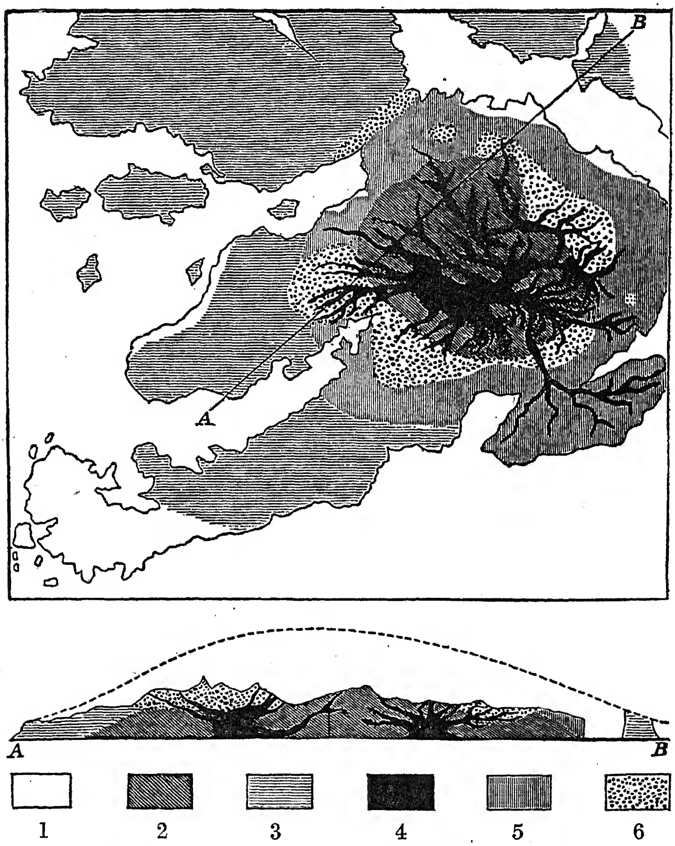


FIG. 137. — Map and section (on *AB*) of the Island of Mull, west coast of Scotland. (After Judd.) 1, Non-volcanic basement beds; 2, granite; 3, basalt flows; 4, gabbroitic dikes; 5, acid flows; 6, volcanic tuffs and breccias. Note the radiating and branching dikes.

Intrusive Sheets or Sills. — In many regions of the world we find sheets of basalt and other igneous rock, the chemical and mineralogical characters of which indicate that they were formed by the cooling of a magma, often with considerable slowness, and which are interbedded with rocks of a clastic character, the latter evi-

dently of non-volcanic origin. Some of these have been intruded between the layers, but in other cases igneous sheets of this type may be old flows, which were poured out over a surface composed of horizontal strata, and which were subsequently covered by other strata of non-volcanic origin. It is important that the two types be distinguished. In the cases of interbedded lava sheets, we should expect to find evidence of this succession of deposits (stratification) not only in the igneous sheet itself, but also in the enclosing rock.

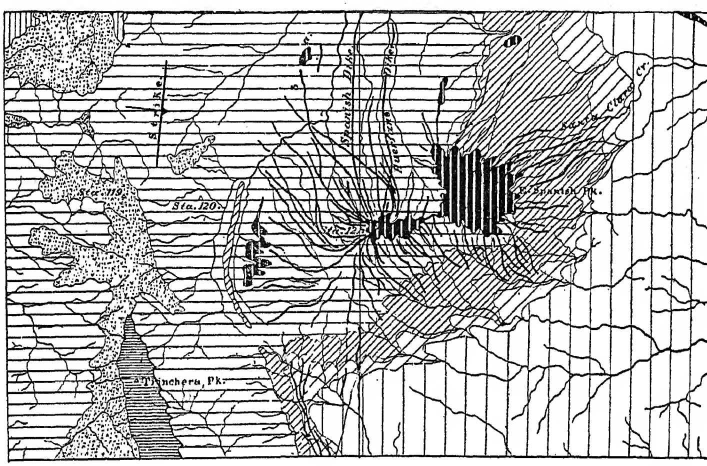


FIG. 138. — Map of a part of the Spanish Peaks region, Colorado, showing the numerous dikes radiating from the volcanic necks or ancient centers of volcanic action. (See Figs. 131, 132, pp. 189, 190.)

Lava streams have very definite and recognizable surface characters, as we have seen, and these are different from the structures found in the bottom of the sheet. In most cases, not only is the surface form of a sheet distinct (ropey, pillowy, rough, etc.), but the lava itself is compact, or even glassy near the surface, and commonly layers of steam holes, either empty or filled secondarily by mineral deposits, are found for some distance down from, and parallel to, the surface. The structure of the enclosing rock also is distinctive, for whereas the under layer over which the lava was poured out shows some effect from the heat of the stream (metamorphism), and may actually have furnished fragments which are included in the lava mass, the overlying layer will show no such contact phenomena, for the lava will, in most cases, have cooled

sufficiently, before being covered by sediments, not to produce any such effect. A still more convincing argument of the contemporaneity of the lava flow is furnished when, as is frequently the case, fragments of the lava are included in the overlying stratum, having been broken from the surface of the sheet before or at the time of the deposition of the covering layer. Weathering of the surface of the sheet and the formation of soil layers is also a clear indication of the exposure of the lava sheet for a time before it was buried by sediment. Such old soil surfaces are seen in nearly all of the fine series of ancient lava flows which are to-day exposed on the east coast of Scotland (Fife), and the length of time of the exposure is shown by the fact that roots and stumps of ancient trees (Calamites) are found in these old soils, and were completely buried by the sediments which followed. A succession of such ancient forest beds is found in the series of lava flows exposed by erosion in the Yellowstone National Park (Fig. 139).

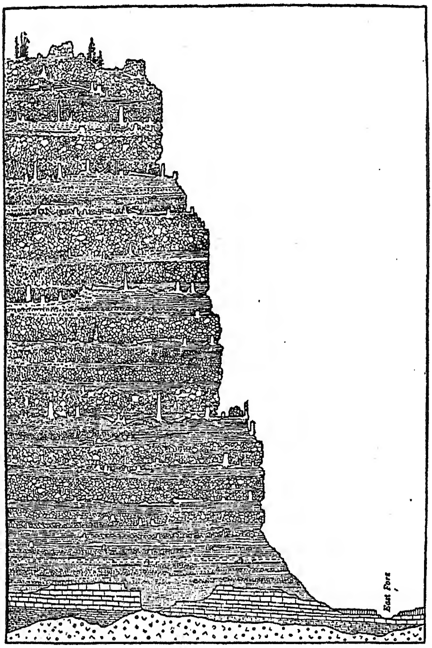


FIG. 139. — Section of Amethyst Mountain, Yellowstone National Park. The mountain consists of a base of Archæan granite and Carbonic limestone, overlain disconformably by 2700 feet of Tertiary strata, chiefly of volcanic origin. The coarse beds are conglomerates and breccias, and alternating with beds of finer material are sandstones and shales bearing the abundant silicified remains of fossil forests. There are at least fifteen successive forests, indicating that number of volcanic outbursts, separated by sufficient time to allow the growth of forest trees varying in diameter of trunks from two to ten feet. (After Holmes.) For photograph of several of these trees see illustration in Chapter XLV.

Intruded igneous sheets or sills, however, show not only a basal but also an upper igneous contact, and, indeed, may include frag-

ments of the overlying as well as the underlying strata. Moreover, the sheets themselves show a similar fine-grained or dense character on both surfaces, while toward the center they become more coarsely crystalline. Such sheets are evidently of more recent origin than the enclosing rocks, and were intruded between and parallel with them, forcing them apart, and cooling thus within the earth's crust without ever reaching the surface. Such intrusive sheets are also called sills,[1] and they are well represented by

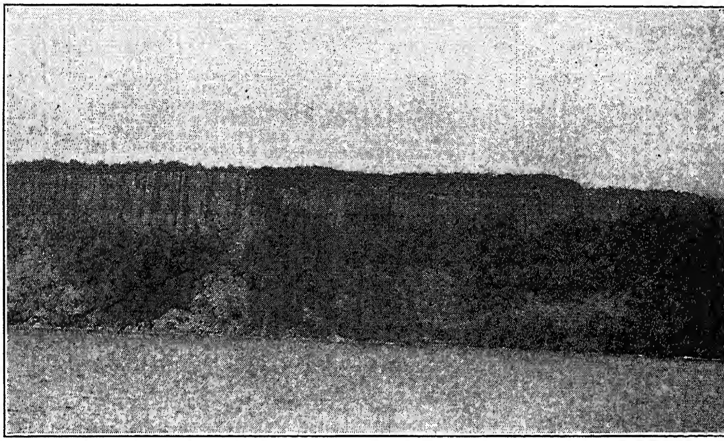


FIG. 140. — Near view of the Palisades of the Hudson, showing jointed trap (simulating columnar jointing) at top and talus slopes below. (Photo by D. W. Johnson.)

the rocks which now form the Palisades of the Hudson River opposite New York City, though these constitute only a small part of the former extent of the intruded sheet (Fig. 140). This is several hundred feet in thickness and has been traced for a distance of about 100 miles. A similarly extensive example, well known to foreign geologists, and indeed the type from which the term sill has been derived, is the " Great Whin Sill " of the north of England. This can be traced for a distance of 80 miles between the enclosing rocks, its resistance to erosion helping to produce the great cliff known as the Pennine escarpment, which bounds the Vale of

[1] The name *sill* was originally applied by the miners in the north of England to any prominent or hard projecting bed or stratum. The type of the volcanic sills is the great *Whin-sill* of northern England mentioned below, this being a prominent bed or sill of whin-stone, a name given to any hard, fine-grained rock, such as basalt, quartzite, etc.

Eden on the east (Fig. 141). This sill varies from 20 to 150 feet in thickness, the average being from 80 to 100 feet, and it forms a prominent ledge wherever exposed in section (Fig. 142). It covers an area probably not less than 1000 square miles in extent. Other sills, mostly of lesser thickness and extent, are found in widely distant regions of the world. Among these may be mentioned the one forming Salisbury Crags in Edinburgh, Scotland, which overlooks Holyrood Castle, and which figured in the disputes over the origin of basalt in Werner's time (Fig. 143 *c*).

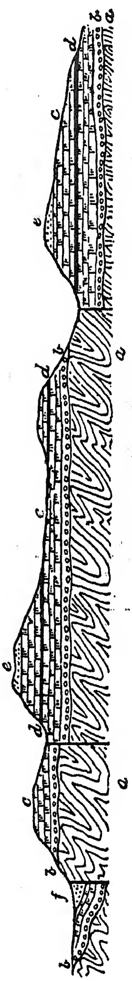


FIG. 141. — Diagrammatic section across the Pennine chain from the Eden Valley to the River Tees, showing block structure. *a*, lower Palæozoic rocks; *b*, basement conglomerate of the Mississippian; *c*, Carboniferous limestone (Mississippian); *d*, Whin Sill; *e*, Millstone Grit; *f*, Permian and Triassic of the Vale of Eden. (After Lake and Rastall.)

Through erosion, the sill is exposed in various ways as shown in the following diagrams (Fig. 143). Sills which were originally intruded between horizontal strata may become inclined by the arching of these strata, as in the case of the Palisade sill (Fig. 143 *a*), or they may even become folded with the strata.

A characteristic feature of sills, and one which aids greatly in distinguishing them from contemporaneous flows, is seen in the lack of absolute conformity to the enclosing strata. Though in any given locality this conformity may be unquestioned, it will be found that on tracing the sill for some distance, it generally breaks across some of the layers, passing either to a higher or lower level, and there continuing for a time parallel to the enclosing strata (Fig. 144). The rocks of the sills are generally massive or not very coarse-grained, though those of the center of large sills, such as that of the Palisades, are sometimes of moderate coarseness. They are generally darker-colored and denser-grained on both upper and lower margins, and the change in grain toward the center is often a very regular one. In the tunnels which have been cut through the Palisade sill, it has

been possible to ascertain, from the size of the grain, the distance from the upper or lower margins at any selected locality. Columnar structure is not a characteristic feature of sills, the apparent

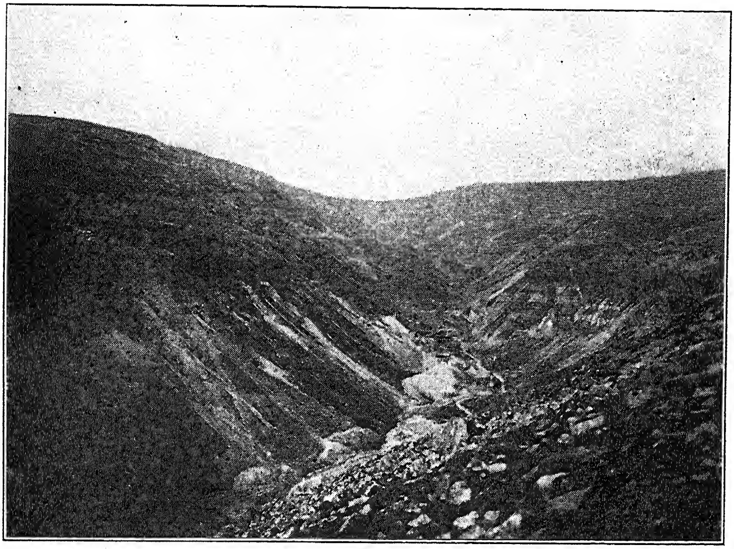


FIG. 142. — View looking up Hilton Beek, northern England, showing the out-crop of the Whin Sill, which forms the prominent cliff on either side, and rests on Carboniferous limestone. (Photo by the Author.)

columnar structure of the Palisade sheet being due to a series of subsequently formed intersecting fissures or true joints.

Laccoliths. — The Henry Mountains of Utah represent remnants of a peculiar type of intruded mass which, instead of spread-

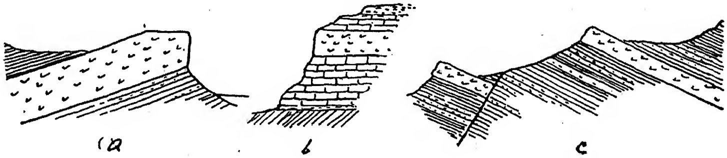


FIG. 143. — Diagrammatic sections of volcanic sills. *a*, Palisades of Hudson; *b*, Whin Sill, North England; *c*, Salisbury Crag in Edinburgh, Scotland.

ing out between the strata, is localized, each separate intrusion swelling into a semi-lenticular or dome-like mass, space for which is made by the lifting into an arch of the rocks which overlie the

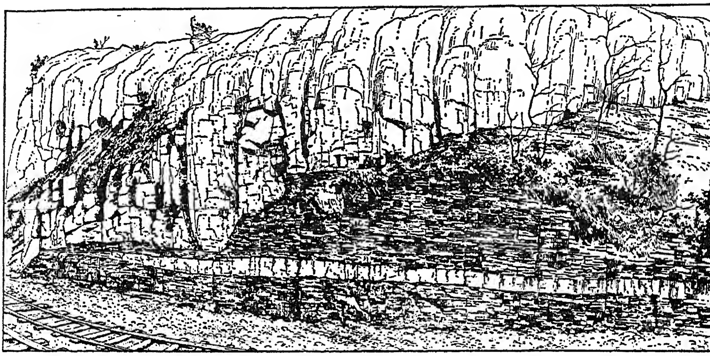


FIG. 144. — Base of Palisade diabase, showing lateral ascent of the diabase across the strata of the Newark group. Kings Point, Weehawken, N. J., looking west. (From photographs, U. S. G. S.)

intruded mass (Figs. 145, 146). These structures were first described by an American geologist, the late G. K. Gilbert, and the type was by him designated a laccolith. Other laccoliths

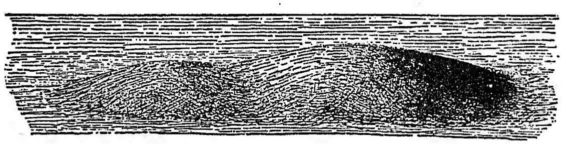


FIG. 145. — Ideal restoration of the laccoliths of Mt. Holmes, Henry Mountains, Utah.

have since been found in many parts of the world, the best known examples among these being in Colorado and Montana. Laccoliths become visible by the erosion of the covering rock, and

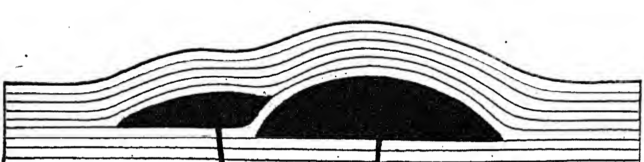


FIG. 146. — Ideal cross-section of the laccoliths of Mt. Holmes, after restoration.

then they constitute hills of igneous material, thick in the exposed center, but thinning away in all directions where they pass beneath the remnants of the original covering sheet or interpenetrate

it in a series of wedges (Figs. 147, 148). It is important to bear in mind that where the contact of the thin edge with the cover-

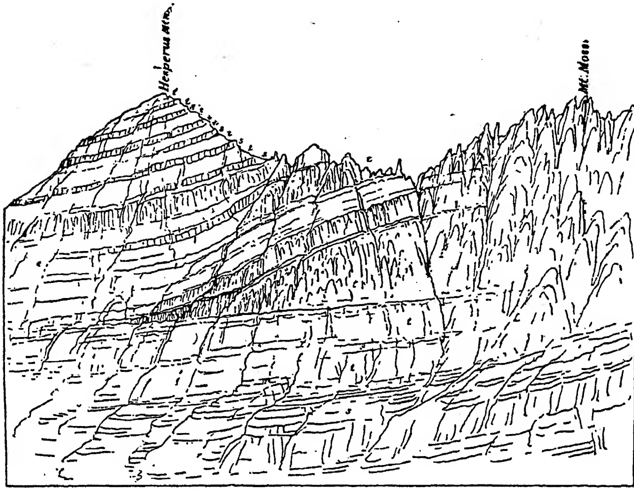


FIG. 147. — Hesperus Mountain, showing wedges and sheets of trachyte intruded into the shales, from the laccolith of Mt. Moss.

ing rock is exposed around the margin of the hill, this contact is seen to be an igneous one, clearly proving the rock to be intrusive. Moreover, it must be shown that the igneous rocks rest upon rock

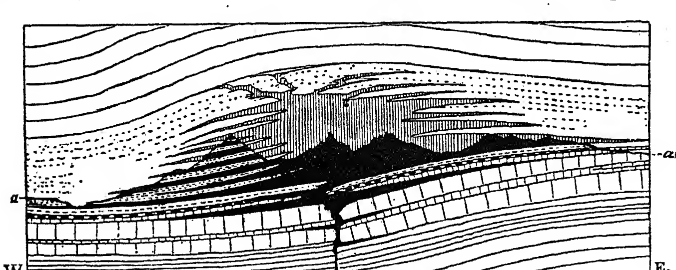


FIG. 148. — Ideal section of La Plata Mountain, Colo., showing the supposed original form of the laccolith of Mt. Moss. The line *a*, *a* is the present profile which cuts Hesperus Mountain and Mt. Moss.

of a different type, and that they are not deep-seated igneous masses which have eaten their way into the overlying rock (bosses, etc.). When a laccolithic intrusion has been completely isolated by erosion so that no part of the original mass is in contact with the overlying

rock, the recognition of the laccolithic origin of the mass becomes very difficult, and the proof of such an origin is sometimes inconclusive. The Mato Tepee or Devil's Tower of Wyoming (Fig. 111, p. 168) has also been interpreted by Jaggar as the remnant of a laccolith rather than a volcanic neck.

Small laccoliths may be exposed in cross-section in a cliff, when their character is undoubted. Laccoliths range in maximum thickness from less than a hundred to several thousand feet, and their diameter varies from a few hundred yards to several

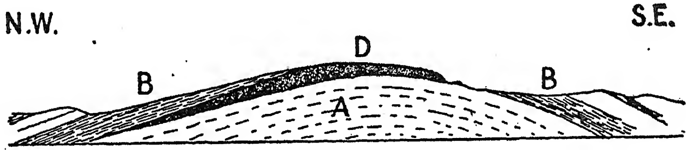


FIG. 149 *a*. — Section of Corndon Hill, in Shropshire, England; the type of the phacolith. (After Harker.)

miles. As in the case of sills, which may be regarded as the extreme in one direction of laccoliths, the upper and lower margins are generally finer grained and may be darker-colored and lower in silica content, besides being richer in ferro-magnesian minerals, than the center. Columnar structure is sometimes developed, the columns standing vertically. This is shown in the Mato Tepee, already referred to as probably an erosion remnant of a thick laccolith.

Phacoliths. — Corndon Hill of Shropshire, England (Fig. 149 *a*), appears to represent a peculiar form of lenticular igneous intrusion in which, however, instead of forcing the overlying strata upward into a dome, these masses occupy the axes of both upward (anticlinal) and downward (synclinal) folds of the enclosing strata. These cavities, it is inferred, were formed as the result of the spreading of the strata by lateral compression during the folding, and thus the igneous masses merely occupy the spaces made for them by other agencies, instead of actively forcing the strata apart (Fig. 149 *b*). Or it may be that the compression of the stratified rocks into folds produced lines of weakness along which the igneous mass

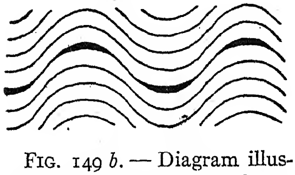


FIG. 149 *b*. — Diagram illustrating the formation of phacoliths. (After Harker.)

found it easy to enter. Such types of intrusions have been called *phacoliths* (Harker) (Greek *phacos*, φακός, a lentil).

Chonoliths. — Another type of this intrusion has been described from the Aletschhorn, a mountain in the Aar Massif of the Alps, and from Ascutney Mountain, N. H. Here, during the folding of the strata, there were formed irregular, instead of lenticular, cavities into which the lava from below found its way. To a greater or less degree the igneous mass may also have forced apart the rock in an irregular manner, partaking of the characters of both the laccolith and the phacolith. The most striking feature of such

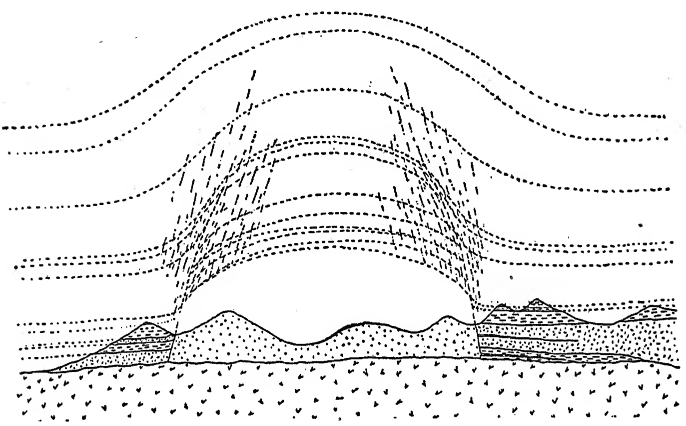


FIG. 150. — Section of the Mt. Holmes bysmalith. (After Iddings.)

an igneous mass is, however, the great irregularity of the spaces which it occupies. To such masses the name *chonolith* (*choanolith*) has been applied by Daly, because the cavities formed, acted as a mold into which the igneous rock was poured (Greek *choanos*, χόανος or χῶνος a mold). It is obvious that small intrusions of this type grade into igneous veins.

Bysmaliths. — Still another type of igneous intrusion has been found in the old volcanic center of the southern end of the Gallatin Range in the Yellowstone National Park in northwestern Montana (Fig. 150). Here the mass which forms Mt. Holmes has the nature of a huge core, resembling a giant volcanic neck, but connected either with no surface flow, or with flows of only secondary significance. It is a laccolith in which the upward force was so great as to rupture the overlying rock mass, and carry it upward for a great

distance. This is therefore a large *plutonic plug* or core which has forced its way upward as a compact mass into the overlying rock, and the contact of this mass with the rocks around its margin shows the evidence of such upward movement. On this account it has been called a bysmalith[1] (Iddings), a rock rising from the depths (Gr. βυσσός, the deep). A bysmalith represents the other extreme of laccolith formation, with the exaggeration of the vertical dimensions. Bysmaliths are also called plutonic plugs in distinction from volcanic plugs, which are the filling of pipes that reach the surface. They differ from stocks in the manner of origin, having forced their way into the rock by lifting the obstruction in their path, while stocks are intrusive into fissures, which they may widen and alter by pressure and otherwise.

It is evident that the recognition of the particular type of igneous intrusion which any given mass represents, can only be determined from careful examination of both the mass itself and of the enclosing rock, and that many cases may occur where erosion has rendered the interpretation at best a doubtful one. If the student keeps in mind the types here given and the essential characters of each, he may, by elimination, in most cases be enabled to reach a conclusion regarding the nature of an igneous mass with which he becomes confronted in the field. Extended examination of all the exposed parts, however, and especially of their contacts with the enclosing rock, will be necessary before such an interpretation is possible.

It must be emphasized again, that the types so far discussed show, from the nature of the rock, that they have cooled at some depth below the surface, but that they do not belong to the great mass of deep-seated igneous material which formed the reservoir, so to speak, from which these intrusions were fed. This group of deep-seated rocks will be discussed in the next section.

Deep-Seated or Abyssal Igneous Masses

In many portions of the world, especially in such regions of ancient rock as eastern Canada, the Adirondack Mountains, parts of Sweden and Finland, and elsewhere, igneous rocks of coarse grain (holocrystalline) are found, which may be interpreted as a part of the reservoir of igneous material from which ancient volcanoes

[1] More corrrectly *byssolith.*

were fed, and from which the other types of intrusions (the hypabyssal) emanated. That these are now exposed upon the surface is due to prolonged erosion, which has removed great thicknesses of overlying rock beneath which the magma cooled. At the same time these igneous magmas forced or ate their way to some extent into the overlying rocks, which, therefore, when still preserved, show an *igneous contact*, that is, a contact of a cool with a molten rock mass. These igneous masses consist of granite, syenite, diorite, gabbro, or of the more basic types of rocks, and they have been divided on the basis of their form and size into bosses and batholiths.

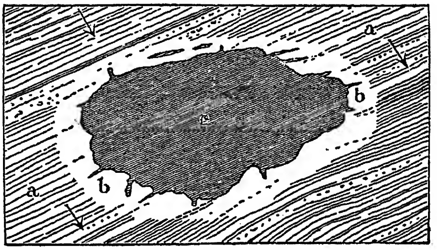


FIG. 151. — Ground-plan of a granite boss, with the ring of contact metamorphism. *a*, sandstones, shales, etc., dipping at high angles in the direction of the arrows; *b*, zone or ring within which these rocks are metamorphosed; *c*, granite, sending out veins or apophyses into *b*.

Bosses. — These are deep-seated igneous masses which show a dome-like surface rather than the form of a plug, and their section as revealed by erosion is a more or less circular one (Fig. 151). They are surrounded by other rocks, often sediments, which show alteration from contact with the heated igneous mass, and such alteration appears often in concentric zones around the boss, the most strongly altered zone being next to the igneous mass.

Batholiths. — These are huge bosses of very irregular form, the exposure of which can sometimes be traced over many square miles. They are particularly characteristic of the older parts of the earth's crust, and they have a very variable relation to the rocks into which they are intruded. The granite headlands of Cape Ann, Mass., of Mount Desert, Maine, and of Halifax, Nova Scotia, are examples of more or less eroded rock masses of this type.

Since these masses cooled very slowly, they became coarsely crystalline, while the prolonged heat greatly affected the rocks with which they came in contact. In batholiths, as in bosses, we may generally trace a series of zones of alteration in decreasing intensity from the igneous mass outward, those immediately in contact with

the igneous mass showing most profound alteration, while each zone generally has developed minerals peculiar to it.

Subordinate Igneous Masses

Apophyses. — This name is applied to offshoots from any intrusive igneous mass whether a dike, sill, laccolith, or deep-seated magma. Apophyses are generally irregular in form and die out in a short distance. Sometimes they may have the character of small dikes for some distance of their extent. They form the surest means of distinguishing an intruded mass from a surface flow.

Contemporaneous Veins. — As all magmas contain more or less water-vapor, this may become locally segregated during the process of solidification by crystallization of the magma, thus rendering portions of the magma very fluid, because of the abundance of the water in it. If the main mass of the magma which has already solidified but is still highly heated, is fissured, as may happen especially near the margin of the mass, this more liquid magma will flow into the fissures, and there solidify. Because the acidic mineral combinations will be the last to form, these *contemporaneous veins*, as they are called, will consist of increasingly lighter minerals, toward the outer part of the cooling mass. Thus it will happen that a magma which solidified to form a dark, dioritic rock, for example, will become intersected near its margin with irregular veins of light-colored rock, consisting mainly of orthoclase, feldspar, and quartz, and still farther, near the margin, by more or less pure quartz veins. This is well shown in the rock ledges of the Massachusetts coast some distance north of Boston, where such a dark dioritic rock is interpenetrated in all directions by veins filled with a pinkish, fine-grained, granitic rock (chiefly orthoclase and quartz), forming a very striking contrast, from which that portion of the coast has received its name of "Marble Head."

Pegmatite Veins. — By the local concentration of much water-vapor and the gases from the solidifying of the main mass of the igneous body, exceptionally fluid magmas may be produced which contain much silica and the substances which go to make up the acid minerals, together with the rarer mineral substances of igneous magmas. This very fluid magma will occupy fissures and cavities in the main mass, from which it is differentiated, and will also be injected into fissures in the adjoining rock. Slow solidification

produces coarse crystals, often many feet or yards in diameter, and these will be largely the more acidic (potash and soda) feldspars, the lighter-colored micas, and much free quartz. Such a coarse rock of acidic minerals is known as a pegmatite, and in it the intergrowth of quartz within the feldspar produces the peculiar structure known as *graphic or pegmatitic structure* (see p. 97, Fig. 40). Rocks of this type are known as *pegmatites*, but they are not always of such coarse texture. In size too, the pegmatite masses may vary from dike-like intrusions hundreds of meters across, to veins only a few millimeters thick. In such pegmatites there are commonly found many minerals formed of the rarer elements, most common among which are tourmalines (commonly the black variety, but also the red, green, or blue gem types), huge crystals of spodumene, of beryl, etc., and not infrequently many metals as well.

Contact of Igneous Masses with Other Rocks

Igneous Contact

By the term igneous contact we mean the junction which has been produced by a mass of igneous magma while still hot with the rock over which it is poured out, if it is a lava, or with the rock of the earth's crust into which it is intruded. In the first case the cold rock over which the lava flow is poured is called the *basement rock*, in the second case the rock into which the igneous mass is intruded is called the *country rock*. In either case the older rock may be assumed to have been cold when the hot magma came into contact with it, and the structures which have resulted from such a coming together of highly heated with cold rocks, are contact phenomena, and the alterations produced in either rock are called *contact metamorphism.*

In the case of surface flows of lava, the phenomena of contact metamorphism are seen only at the base of the lava sheet, though a certain change is produced where the surface of the sheet is in contact with the atmosphere, or with water in the case of a submarine outpouring of lava, and these changes in the lava sheet may also be referred to as metamorphic changes in a very literal interpretation of the term.

Contact metamorphism is very slight in the case of most intrusive sheets or sills, in laccoliths, and generally in dikes, though in the case of such large sills as the Palisades it may extend for many

yards from the contact. In all cases it must be remembered that in intrusive masses the contact phenomena are found on all sides of the intruded mass. Around volcanic plugs and stocks contact phenomena are well marked, especially in the former, where there was continuous or repeated passage upward of igneous material with surface eruption. Again, where dikes are numerous and close together, much contact metamorphism is observable. But such phenomena are most marked in the large, deep-seated igneous masses of coarse grain, which cooled slowly and which, therefore, subjected the adjoining rocks for a long time to the heat of the igneous body and the action of the gases given off from it.

Kinds of Contact Metamorphism

We may distinguish two kinds of contact metamorphism, that produced upon the igneous mass itself from contact with a cool wall rock, and that produced upon the wall or country rock. The first is spoken of as an *endomorphic*, and the second as an *exomorphic*, change.

Endomorphic Effects. — The effect produced by the contact of a magma with the wall or country rock upon the resulting igneous rock itself is in the first place a change in texture along the contact, as we have already seen. This is shown by finer grain or even a glassy character of the igneous rock at the junction with the wall rock. A porphyritic texture with fine ground-mass and coarse phenocrysts may also develop as the result of more rapid cooling. When, however, the enclosing rock is thoroughly heated by the igneous mass, as in a volcanic conduit, no perceptible change may result in the marginal portion of the igneous mass on cooling, while the effects on the wall rock itself (the exomorphic effects) are the more marked.

In the second place, new minerals, not found in the main mass of the igneous intrusion, may be formed near the contact, from the chemical activities of vapors and gases which tend to be excluded from the main mass as it solidifies and to escape toward the margin of the mass and thence into the surrounding rock. In granitic intrusions tourmaline is not an uncommon mineral thus formed.

Exomorphic Effects. — The effects of the heated intrusion upon the wall or country rock are, however, the most marked. Among

these the most notable are the baking or hardening and toughening of the rock near the contact, from the heat, and its frequent change to a more crystalline condition. Next in importance is the development of new minerals on the contact zone, these being generally formed by the chemical activity of the gases and vapors which enter the rock and constitute the *mineralizers*.

The width of the zone subject to contact metamorphism varies with the size and the heat of the igneous mass, and with the amount of mineralizing gases and vapors given off. It also varies with the character of the enclosing rocks, some being more easily altered than others, while some are more permeable to heat and mineralizing vapors than others. In general, older igneous rocks into which younger ones are intruded, are less altered than are sediments of chemical, organic, or clastic origin, in which the chemical composition is such as to permit ready change, or in which the conductivity, texture, and other characters allow easy entrance of the heat and the vapors. The special effects on a few types of these may be noted.

Effects on Limestones. — Limestone is the general name applied to rocks consisting of carbonate of lime or of carbonate of lime and magnesia. They may be of aqueous (chemical), organic, or of clastic origin, as more fully discussed in later chapters. Limestones are seldom pure, there being commonly an admixture of clay or of silica in the form of flint, chert, intimately admixed grains (sand), or other particles. The first and most general effect of the igneous mass upon limestone is the crystallization of the latter, with the result that a *marble* is produced. Great masses of marble are, however, not produced in this manner, but by more extended (regional) metamorphism, during mountain-making disturbances (see Chapter XX). Changes in the mineral character also occur by recombination of the various substances present. Thus if silica is present, the lime will combine with it, with the separation of carbon dioxide, and a lime silicate (the mineral wollastonite) is produced. The change may be expressed in the following formula:

$$\underset{\text{Carbonate of Lime}}{CaCO_3} + \underset{\text{Silica}}{SiO_2} = \underset{\text{Lime silicate (Wollastonite)}}{CaSiO_3} + \underset{\text{Carbon dioxide}}{CO_2}$$

If the limestone is magnesian, then a double silicate of lime and magnesium is produced, this giving a mineral of the pyroxene group, known as *diopside*, abundant crystals of which are found in

the northern part of the city of New York (Inwood region), where the magnesian limestones are penetrated by numerous pegmatite dikes (see Fig. 136, p. 193). The formula expressing this change may be written as follows: —

$$\underset{\text{Lime magnesium carbonate}}{Ca\,Mg(CO_3)_2} + \underset{\text{Silica}}{2\,SiO_2} = \underset{\text{Lime magnesium silicate (diopside)}}{Ca\,Mg(SiO_3)_2} + \underset{\text{Carbon dioxide}}{2\,CO_2}$$

When both clay and quartz are present, a double silicate of lime and alumina may result, the aluminum being furnished by the clay. This new compound will then crystallize out in the form of the mineral garnet, while both water and carbon dioxide are given off. The following formula expresses this change: —

$$\underset{\text{Lime carbonate (Calcite)}}{3\,CaCO_3} + \underset{\text{Clay}}{H_4Al_2Si_2O_9} + \underset{\text{Silica (Quartz)}}{SiO_2} = \underset{\text{Lime aluminum silicate (Garnet [1])}}{Ca_3Al_2Si_3O_{12}} + \underset{\text{Carbon dioxide}}{3 \cdot CO_2} + \underset{\text{Water}}{2\,H_2O}$$

Good illustrations of the formation of garnets, sometimes of considerable size and in large numbers, but of no great value, may be seen in the impurer parts of the same limestones (Inwood marble) in the northern part of New York City, near the contacts with dikes.

Many substances may be carried into the limestones by gases and vapors, and so produce a variety of minerals. Those mentioned are, however, the most important.

Effects on Mud-Rocks. — This is a general name applied to sediments composed most commonly of microscopic particles of quartz and of clay, sometimes the one and sometimes the other substance predominating. Lime particles may also be very abundant and intimately disseminated among the clay and quartz, and other substances in a fine state of division may also occur. Such mud-rocks may be massive, or they may have a fine and irregularly bedded or laminated structure, when they are called *shales*. By baking along the contact, such a mud-rock may be changed into a dense mass comparable to artificially baked clay (porcelain), forming a rock called *porcelanite* (*porcellanite*) or a *hornfels*, which may have the appearance and hardness of a dense basalt or other igneous rock and may be mistaken for such. Another feature produced in such mud-rocks, a short distance from the contact, is a series of spots or knots of mineral matter or even of crystals of

[1] This is the variety Grossularite. There are several others of different composition. See Table, p. 62.

minerals, among which the commonest is a silicate of alumina known by the mineral name of *andalusite* (Al_2SiO_5); other minerals may also be developed.

Effect on Quartz Rocks (Sandstones, etc.). — When the country rock consists largely of quartz, commonly in fine grains (sandstone) the effect of the intrusion of an igneous mass is not so marked as in the case of other rocks. Close to the contact, the sandstone may be hardened into a *quartzite*, and if clay, lime, or other mineral substances are present, new minerals may be produced.

Alteration by Gases and Vapors

Where the volcanic activity has subsided into the solfataric or fumarolic stage, with the emission only of vapors and gases, the country rock around the vents and along fissures penetrated by these gases and vapors may be profoundly altered. New minerals may be produced in this zone of alteration and deposits of older minerals may be enriched by the addition of new material from the gases and vapors. In this wise, important mineral and ore deposits may be produced, to some of which reference will again be made in a later chapter.

Ancient Igneous Masses in Sedimentary Contact with the Overlying Rock

The granite mass of Pikes Peak, in Colorado, differs from the granite masses previously discussed in the fact that the contact with the overlying rock is not an igneous, but a sedimentary one. To be sure, when the granite was formed by the cooling of a deep-seated igneous magma, it was in igneous contact with the overlying rocks of that time. But these covering rocks were entirely removed by erosion, and later sediments (sand, then limestone) were spread over the eroded granite surface, and at a much later date still, after the core of the Rocky Mountains was elevated, these younger rocks were again partly removed by erosion, and in the various cañons which cut the lower slopes of the mountains these sediments are seen to rest upon the eroded surface of the granite (Figs. 152, 153).

Evidently the relationship thus seen between the granite and the sediments does not permit our classifying the Pikes Peak granite mass as belonging to any of the igneous types so far discussed, and

the name *abyssolith* has been proposed for it by Grabau. An abyssolith, then, is a mass of rock, generally granite, or one of the more basic rocks of this type, which was originally a boss, or a batholith, or may even have been a bysmalith, laccolith, or stock, which has been exposed by erosion, then covered by sediments which are, of course, unaffected by the igneous mass because it was cool at the time, and after a more or less domelike uplift the sediments were again eroded from the surface of the dome, re-exposing the igneous core around which unaltered sediments crop out. In addition to the Pikes Peak region we may note as an example of this type the Black Hills Dome, with its center of old igneous rocks. Many small

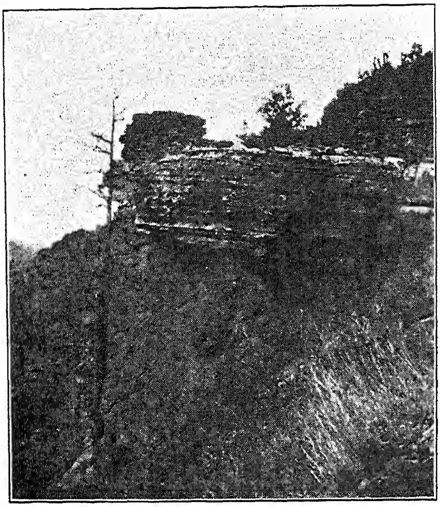


FIG. 152. — Contact of the stratified basal Palæozoic beds and the granitic basement rock of the Pikes Peak mass, in Williams' Cañon, Colorado. (Photo by Author.)

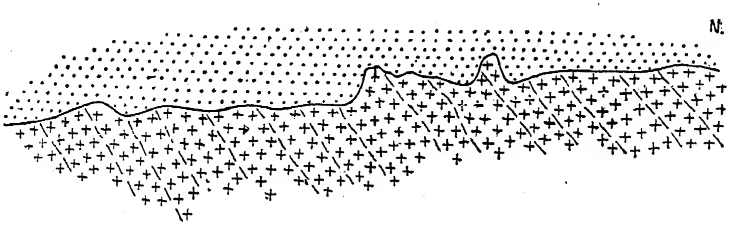


FIG. 153. — Details of contact of Palæozoic sediments and Pre-Palæozoic granites in Williams' Cañon, Colorado. (After Crosby.)

examples of such resurrected igneous rocks of dome-like form surrounded by unaltered sediments are known from this country as well as from Europe.

Relative Age of Igneous and Enclosing Rock

If we then recognize the nature of the contact between an igneous mass and the sediments which once covered it, we can determine the relative ages of the two series. If the contact is igneous, the sediments are older than the intruded igneous mass. If the contact is a sedimentary one, the igneous mass is the older, and there is a long-time interval lost, between the two — an interval during which erosion removed the older covering rocks, with which the mass was in igneous contact, and this erosion occurred before the sediments now seen in contact with the igneous mass were deposited. This shows how important it becomes to determine whether a contact is igneous or sedimentary.

CHAPTER X

THE AQUEOUS OR HYDROGENIC ROCKS

General Character and Varieties

Source of the Material. — Practically all natural waters contain mineral matter in solution, the common illustration being ocean water, every liter of which contains about 35 grams of mineral matter, more than 27 grams of this being common salt (sodium chloride), which means that every cubic mile of sea-water contains about 131,526,000 short tons of this important substance in solution. Sea-water is therefore spoken of as *salty* or *saline*, and this saltiness is readily recognized by taste. The other dissolved substances are also called salts, but their presence is not so readily recognized. Some water bodies, like the Baltic Sea, contain only one fourth or less of this amount of salts in solution, and such waters are called *brackish*. The waters of the Hudson River some distance above New York City are brackish, because they are formed by a commingling of the fresh water from the upper river with salt water entering from the sea.

When the water contains so little substance in solution that it can be used for drinking purposes (whether it is contaminated by organic matter or not) it is called *fresh water*, but fresh water in nature always contains some substances in solution, lime usually predominating, this when present in sufficient quantity forming *hard water*. When carbonate of soda and similar substances are present in such quantities as to render the water unfit for human consumption, it is called *alkaline*, and all travelers in the semi-arid regions of western North America are familiar with such water. Finally there are water bodies like Great Salt Lake, the Dead Sea, and others, in which the quantity of common salt in solution exceeds many times that in the ocean water, and such waters are spoken of as *super-saline*, or as *brines*. Brines may also be produced by partial evaporation of ocean water, just as brackish waters are produced by the dilution of ocean water.

Separation of Material. — When the substances which waters hold in solution are separated out so as to form solid material, this material constitutes rock masses to which in general we apply the name of *salts*, after the example of the commonest of these, the ordinary salt. If the separation is produced by organisms, the product is called organic salts, and these belong in the division of organic or biogenic rocks, where they will be discussed. If the separation is by inorganic activities, the product is a normal aqueous or hydrogenic rock, to which the present chapter is devoted.

Separation by inorganic means is accomplished in a variety of ways, of which the following are the most important:

1. Separation by the condensation or complete evaporation of the water by heat, drying winds, etc., during which process a stage is reached when the water becomes *saturated*, that is, it holds in solution as much of a given salt as it can hold for that temperature and pressure. If that stage is passed, the excess of salt separates out, often in a more or less crystalline form. The point of saturation varies with the nature of the salt, and when two or more salts are present in the solution, they will not only have separate and distinct saturation points, but the presence of each is likely to influence the saturation point of the others, either lowering or raising them. Complete separation of all the salts will occur upon complete evaporation of the water. Such salts are called evaporation products, or briefly, *evaporates*.[1]

2. Separation of salts from the solution by the force of attraction which crystals or particles of mineral matter exert on material of the same kind in the solution (generally a saturated one) in which those crystals or particles are immersed.

3. Separation by the abstracting of the solvent or substance which holds the salt in solution.

4. Separation by chemical reaction between minerals in solution in the water, and other substances introduced from extraneous sources, either as gases or as solutions, and the consequent formation of new and less soluble compounds which are then precipitated.

5. Separation by electrolysis.

[1] Strictly speaking, this is also a chemical combination of the dissociated *ions*, which occurs at the moment of solidification. Such salts are therefore also precipitates, but it is well to keep this type distinct from that resulting through reactions with newly

As illustrations of the first class we may cite the separation of salt when sea-water is evaporated or when incrustations of salt are formed from a solution of that substance which is allowed to stand for a time in a warm room. The second method is illustrated by the crystallization of the alum of a saturated solution around a crystal of alum introduced into that solution, or the formation of rock candy from a saturated solution of sugar. Precipitation through abstraction of a solvent is shown by the deposits of lime on the inside of boilers and tea-kettles where "hard" water is used, the solvent, which is carbon dioxide, being driven off by the heat. It is also shown by the precipitation of lime around the mouths of springs, in which the water escaping from under pressure loses some of the carbon dioxide which was the solvent of the lime in the water. Examples of precipitation of salts by the addition of substances in solution which by chemical reaction produce a less soluble compound, or by the passing of gases through a solution, are familiar to all workers in chemical laboratories, while the electrolytic method is one much practiced in the arts.

The first three methods cited are most commonly observed in nature. The precipitation by the addition of reagents, whether liquid or gaseous, is chiefly found in the formation of lime deposits under the influence of ammoniacal gases. Since these are, however, in nearly all cases produced by the direct activities or the indirect influence, through decay, of organisms, such deposits are best referred to the organic or biogenic group, and they will be discussed there in this book. Electrolytic processes in nature are still little understood, but that they are going on cannot be doubted. Some of the inclusions of salt in the pore spaces of marine sediments have been explained in this manner.

Most precipitates from an aqueous solution are called salts, no matter how they are formed or what their composition. There are, however, some simpler substances, such as the oxide of silicon or silica (SiO_2) and others, which cannot properly be called salts. (See Chapter IV.) One of the essential characteristics of a salt is its purity of composition, though it is true that under certain conditions precipitation of several salts may take place simultaneously, thus producing what is called a *eutectic mixture*. When pure, the material is in reality a single mineral mass, as for example, the mineral Halite or rock salt; but because of its extensive development it is treated as a rock.

Classification of aqueous precipitates according to composition. — It is evident that chemical composition is the primary basis on which aqueous precipitates must be classified. Furthermore, most salts look very much alike except when they are crystallized, or when, as in special cases, color, hardness, and weight make distinction possible. In the following pages will be given some of the more important and common salts and oxides, the classification being made, for the sake of convenience, upon the basic element in the composition.

The Textures of Aqueous Deposits

The texture of aqueous precipitates is either crystalline or non-crystalline — the latter also being designated *amorphous*. Crystals of all sizes and degrees of perfection may form, the most perfect

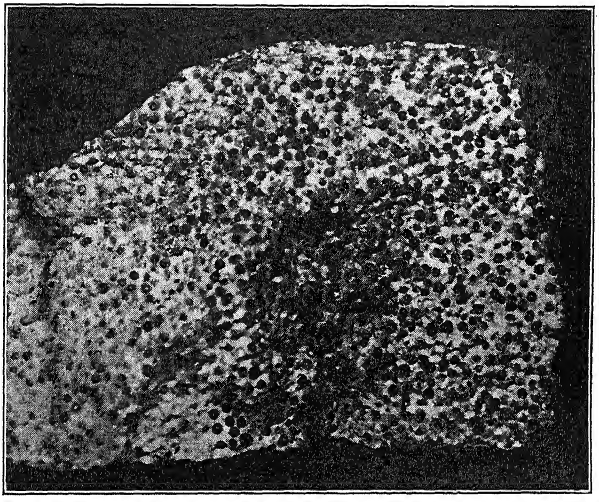


Fig. 154 *a*. — Oölitic limestone silicified. (Photo by B. Hubbard.)

being those least interfered with by other crystals. The amorphous texture may be either in the form of separate or *discrete particles*, which may or may not be tied together subsequently, as in oölites, or it may be a solid or *concrete* mass.

Discrete particles. — These comprise the two following textures:

(*a*) *Oölitic texture* (Fig. 154 *a*, *b*), characteristic of oölites. The particles are small spheres, generally with a nucleus and with radial, or with concentric or zonal, structure, the size suggesting the roe of fish; typically lime carbonate.

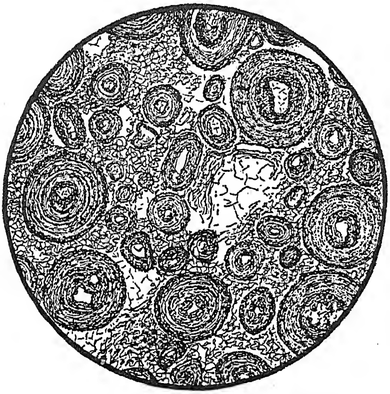


FIG. 154 *b*. — Thin section of Jurassic oölite showing the characteristic zonal structure. Brown Jura, Schönberg, near Freiburg I. B., Germany. Enlarged 24 diameters. (After Rosenbusch.)

(*b*) *Pisolitic texture* (Fig. 155), characteristic of pisolites. The spherules are of the size of a pea or larger. These are also chiefly lime carbonate.

Concrete Masses. — These include the following textures:

(*a*) *Botryoidal* (Fig. 156), with grape-like rounded surfaces.

(*b*) *Banded*, in layers which in section show a banded structure.

(*c*) *Laminated*, in thin layers or laminæ.

(*d*) *Scaly*, composed of small scale-like masses.

(*e*) *Fibrous*, in slender hairlike fibers, often elongated crystals.

(*f*) *Tufaceous* (Figs. 157, 158), porous as in calcareous tufa.

(*g*) *Concretionary* (Fig. 159), in large more or less spherical masses.

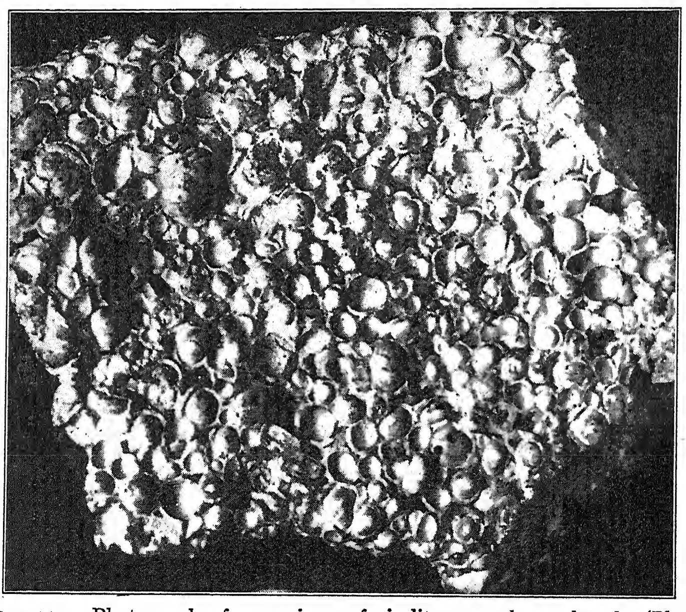


FIG. 155. — Photograph of a specimen of pisolite somewhat reduced. (Photo by B. Hubbard.)

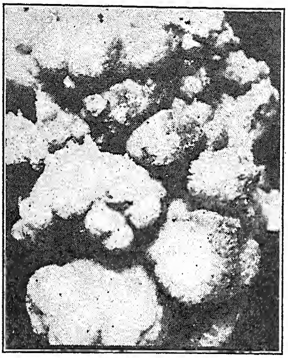


FIG. 156. — Botryoidal structure in calcium carbonate deposits.

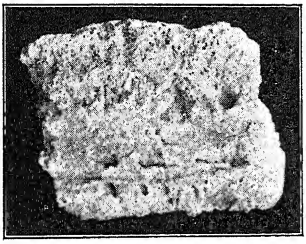


FIG. 157. — A fragment of calcareous tufa. Reduced. (Photo by B. Hubbard.)

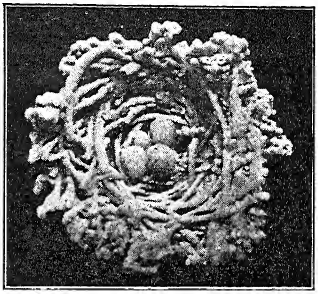


FIG. 158. — Bird's nest and eggs "petrified" or covered with a deposit of lime carbonate, by submersion in tufa-depositing spring-water. Reduced. (Photo by B. Hubbard.)

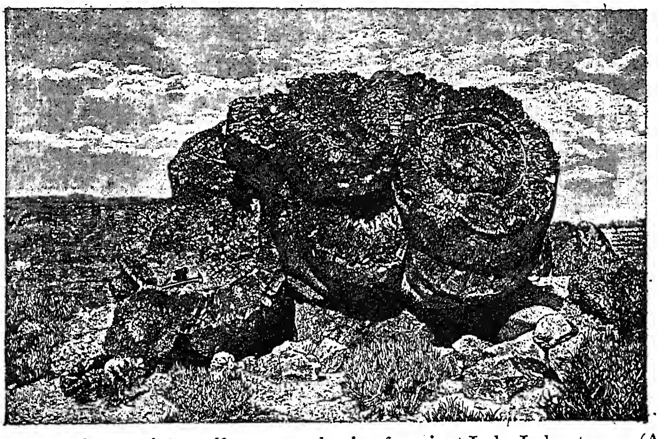


FIG. 159. — Concretionary limestone; basin of ancient Lake Lahonton. (After Russell.)

The Principal Types of Aqueous or Hydrogenic Deposits

Among the many precipitates or other deposits formed directly from aqueous solutions, a certain number is found in sufficiently large quantities to be treated as rock material, while others are important as sources of valuable substances or are themselves of economic value. Their essential mineral characters have already been given in the tables in Chapter IV.

Non-Metallic Aqueous Deposits

Rock Salt. — Chloride of sodium (NaCl). — This is the most important as well as the most abundant mineral substance obtained from ocean water. It commonly occurs in beds, which may have a thickness of a hundred feet or more but generally are only a few feet thick, forming a succession of beds separated by gypsum, anhydrite, limestone, dolomite, or clay, — or more rarely by other mineral matter. Such deposits are formed by concentration of sea-water either in basins cut off from the sea by elevation or by the formation of a barrier, or in lagoons behind a bar with continued supply of sea-water through an inlet, as more fully discussed in the next chapter. Salt is also separated from lake basins in arid regions by the concentration, through partial evaporation, of the water. Finally, salt deposits are formed in desert basins from salt disseminated through the rocks in the rims of those basins, as more fully discussed in the next chapter.

Rock-salt deposits are seldom very continuous, having in most cases a lens-like form. Salt is also extensively manufactured by the evaporation of sea-water in shallow salt gardens or sea salinas, which are located on nearly all shores where the climatic and other conditions are favorable. Natural as well as artificial brines, formed by the solution of old salt beds in the earth's crust, or of disseminated salt, are also extensively used in the manufacture of salt. Salt is mined in central New York, in southern Michigan, in Louisiana, and in a few other localities in the United States. Extensive salt mines exist in Austria, Galicia, Rumania, and elsewhere in the Old World. The salt mines of North Germany are worked chiefly for their potash deposits. Hills or mountains of salt are found in many of the dry regions of the world, — in northern Spain (Cardona), Algeria, Persia, and elsewhere.

The chief uses are for domestic and dairy purposes and for chemical industries.

Gypsum. — Hydrous sulphate of lime ($CaSO_4 \cdot 2H_2O$). — This is a common associate of salt deposits, being found beneath beds of rock-salt of marine origin (sometimes replaced by anhydrite) and always separating from sea-water, which undergoes concentration before the rock-salt separates out. Such rock gypsum is commonly massive and sometimes impure, but pure white gypsum (alabaster) also occurs. It also occurs as crystals (selenite), scattered through mud and sand deposits, especially in desert regions. A fibrous variety (satin spar) occurs in veins. Gypsum is seldom formed in extensive beds in desert regions except

where sea-water evaporates. It is also formed as an alteration product, generally of limestones, by waters carrying sulphuric acid; large beds of gypsum result in this way, those of New York state being an example. Anhydrite deposits are also changed to gypsum when surface waters come in contact with them. Extensive deposits of gypsum are found in the "Red Beds" of the western United States, and in Kansas, Oklahoma, and Texas. It is found in Nova Scotia and in the Paris Basin, where it has been and still is extensively quarried and burned into Plaster of Paris; also in many other parts of the world.

Raw gypsum is ground and used as a natural fertilizer (land plaster), to retard the setting of cement, and for many chemical purposes. When burned or "calcined" at 350° F. it loses most of its water ($CaSO_4 \cdot \frac{1}{2} H_2O$), and is ground into the familiar "Plaster of Paris." When this is mixed with water gypsum is again formed. It hardens rapidly and is used extensively in the arts for molding, statuary, etc., and for stucco work.

Anhydrite. — Calcium sulphate ($CaSO_4$). — This is distinguished from gypsum by its greater hardness and specific gravity. Its color is often also more grayish. It is formed as a primary deposit from sea-water in cut-off basins, especially when the water contains an excess of chlorides. The largest known deposits thus formed are in northern Germany, where they underlie the salt and potash beds. Anhydrite slowly changes to gypsum by taking on water, with an expansion of the mass. It is of little economic importance.

Carbonate of Lime. — Calcite, Aragonite, Limestones, etc. ($CaCO_3$). — The great bulk of the deposits of carbonate of lime, including the limestone beds, is of organic or of clastic origin, but there are a number of lime deposits which belong to the hydrogenic division. The most extensive of these is probably calcareous tufa (Fig. 157), which is formed by springs issuing in limestone regions and depositing the excess of lime which they hold in solution. Calcareous tufa is mostly porous and light, incrusting not infrequently mosses and other plants and also other objects. Some massive deposits of this type, however, are known, constituting the so-called "Mexican Onyx." Compact carbonate of lime deposits are also formed in caves as stalactites and stalagmites. These usually have a banded structure, showing the successive addition of layers. That of the stalactites is concentric around the longitudinal axis, which in the early stages is formed by a delicate tube.

Fig. 160. — Concretionary magnesian limestone (Permian), Durham, England. Much reduced. (B. Hubbard, photo.)

Beds of limestone are sometimes built up from large rounded masses or "concretions," which have resulted from the deposition of carbonate of lime, generally around a nucleus. Sometimes these are formed as original masses of limestone, as in the limestone deposits of Lake Lahonton (Fig. 159), or an older limestone of this type which occurs in the Permian series (Magnesian limestone) of northeastern England (Fig. 160). In other cases these concretions occur in shale beds, forming distinct layers, which when they become confluent by continued growth form bands of limestone. When separate they often

take on disk-shaped or spherical forms, while a series of radial cracks are developed in the interior with the growth of calcite veins. Such concretions are called *septaria* (Figs. 161 *a*, *b*). All carbonate of lime deposits effervesce readily with dilute hydrochloric acid, this being the most distinctive test.

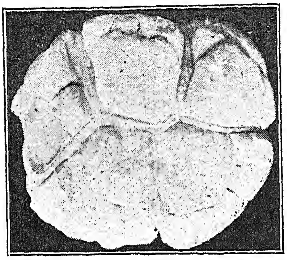


FIG. 161 *a*. — Septarium or Turtlestone. A concretion from calcareous shales. The fissures of the interior were filled with calcite veins, which became exposed after erosion and weathering of the surface of the concretion; about $\frac{1}{4}$ natural size. (B. Hubbard, photo.)

Dolomite. — Carbonate of lime and magnesia ($(CaMg)CO_3$). — This differs from the pure carbonate of lime deposits in its greater hardness and in the fact that it effervesces only in strong hydrochloric acid. It is sometimes a primary deposit in basins where anhydrite is forming, with which it becomes more or less intimately mixed. It may also be formed as an original precipitate in portions of the sea in which the solution has become concentrated. Many dolomitic limestones are, however, of secondary origin, the original magnesia content, which was derived for the most part from calcareous algæ, etc., being proportionately increased through the solution of carbonate of lime by ground water. Secondary deposition of magnesium carbonate also takes place from solutions in the circulating ground water. Pure dolomite contains 54.35% $CaCO_3$, and 45.65% $MgCO_3$.

Magnesite. — Carbonate of Magnesia ($MgCO_3$). — This is harder and more compact than dolomite, and dissolves with effervescence only in hot hydrochloric acid. It occurs as a crystalline mineral, as replacement of dolomite, and also as an amorphous, earthy, hard, compact mineral, probably a colloidal precipitate. It is often concretionary with conchoidal fracture, appearing like unglazed porcelain, this type being usually derived from the alteration of serpentine and other magnesian rocks. Beds of magnesite are found associated with gypsum in fresh-water limestones of France.

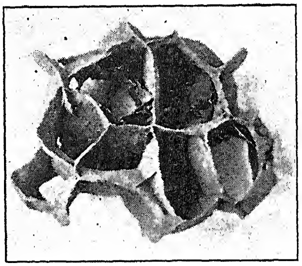


FIG. 161 *b*. — A weathered septarium, showing the mineral, which filled the fissures, left in relief, thus producing the typical "septarium" structure. (Photo of a specimen in Columbia University, by B. Hubbard.)

Apatite and Phosphate Rock. — Although the most extensive deposits of phosphate of lime are of organic origin, there are some that must be considered as purely aqueous or hydrogenic deposits. Among these are the apatite veins and the marine concretions of phosphate around an organic nucleus. Phosphate of lime occurs also as a secondary replacement of limestone. Apatite crystallizes in hexagonal prisms, etc., and is readily recognized by its form, hardness, and color (see Table in Chapter IV). Rock phosphates are generally amorphous and compact. The pure mineral (tricalcium phos-

phate) contains 45.8% of phosphoric acid (P_2O_5). The principal use of phosphate is as a fertilizer.

Potash Salts. — There are a number of evaporation products which are primarily salts of potash and are important sources of this substance. Among the more common of these are *Sylvite*, the chloride of potassium (KCl), a very soluble, soft, transparent, milky reddish or yellowish mineral, commonly mixed with rock salt; *Carnallite*, the hydrous double chloride of potassium and magnesium ($KCl \cdot MgCl_2 \cdot 6\,H_2O$), a colorless or snow-white or variously colored salt, easily soluble, and an important source of potash; and *Kainite*, the compound chloride of potassium and sulphate of magnesium, with water ($KCl \cdot MgSO_4 \cdot 3\,H_2O$), colorless to deep blood-red, and chiefly an alteration product. The chief use of potash is for agricultural purposes and in chemical works.

Trona. — Sodium carbonate ($Na_2CO_3 \cdot NaHCO_3 \cdot 2\,H_2O$). — This is a common evaporation product of alkaline lakes. It is glassy or transparent when crystallized, but usually forms a white salt. Important American localities are Searle's Marsh, Owens and Mono Lakes, Cal., and Soda Lake, Nevada, while some Russian and Hungarian lakes, and the Natron lakes of Egypt west of Cairo, represent foreign localities. It is used for domestic and chemical purposes, but much of the commercial trona is artificially produced. On account of its solubility it is not generally found in the older rocks.

Mirabilite. — (Glauber salt.) — Hydrous sulphate of sodium ($Na_2SO_4 \cdot 10\,H_2O$). — This is a crystalline, granular salt, usually colorless, and readily soluble in water. It is formed, especially in winter, by certain saline bodies, such as Great Salt Lake, Utah, and the Kara Bugas Gulf on the east coast of the Caspian Sea. On the floor of the Kara Bugas a bed of mirabilite, estimated to contain 1000 million metric tons, has formed but it is not yet exploited. In Wyoming and New Mexico occur beds of this salt mixed with epsomite, natron, and common salt (halite). In some cases the deposit is 15 feet thick and covers an area of 100 acres.

Glauberite. — Double sulphate of sodium and calcium ($Na_2SO_4 \cdot CaSO_4$). — This is a white, gray, yellow, or red mineral, a little harder than common salt (2.5–3). It occurs in many playa lakes (Borax Lake, Searle's Marsh, Death Valley), and in the salt deposits of Germany, Spain, Austria, Sicily, etc. It also occurs in a number of Tertiary deposits in Spain.

Soda Niter, Chile Saltpeter. — Nitrate of sodium ($NaNO_3$). — This is a white to reddish brown, gray, or lemon-yellow salt, commonly impure, when it is called *caliche*. It is abundant in the desert tracts of western Chile and elsewhere in South America and other parts of the world.

Borax Salts. — These include *Borax* or *Tinkal*, sodium borate ($Na_2B_4O_7 \cdot 10\,H_2O$), a colorless or yellowish or green to gray, soluble mineral, somewhat harder than common salt; *Colemanite*, the hydrous borate of calcium ($CaB_6O_{11} \cdot 5\,H_2O$), generally a massive, glassy or colorless, more or less transparent mineral, found as a bed from five to 20 feet thick in San Bernardino Co., Cal., and elsewhere; and *Ulexite*, the double borate of sodium and calcium with water ($NaCaB_5O_9 \cdot 8\,H_2O$), which occurs as white balls of fibrous material and satiny luster (cotton balls). Borax salts are found in volcanic regions, such as the

famous "saffioni," *i.e.*, fumaroles, in the volcanic region of Tuscany; in hot spring and lake deposits of volcanic districts, as in Tibet, etc., and the Coast Ranges of California, and in playa deposits, as in Death Valley and elsewhere in the western United States. Colemanite is the chief American source of borax.

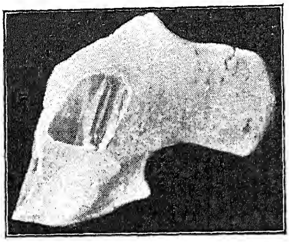


FIG. 162. — Concretion of flint from the chalk beds of England. About one fifth natural size. (Photo by B. Hubbard.)

Silica. — Oxide of silicon (SiO_2) frequently with water. — The most familiar form of this is quartz in crystalline or amorphous form, which occurs in veins, geodes, etc., colorless to variously colored; also as addition to quartz grains in sandstones, enlarging them to fill all the interstices. It occurs extensively as a porous, white, and light spongy deposit of hydrous quartz, around geysers (see Fig. 131, p. 187), and is hence known as *geyserite* or silicious sinter. Again, it occurs as concretions of *flint* in chalk beds (Fig. 162), or as chert nodules or layers in limestone. These types are compact and have a conchoidal fracture, with a black or dark brown color on the freshly fractured surface. Flint and chert are secondary concentrations through solution and redeposition of disseminated silica particles of organic origin. (Fig. 163).

Glauconite. — Greensand. — This is a complex silicate of potassium and iron ($K \cdot FeSi_2O_6 \cdot H_2O$). It consists mainly of dark green grains, generally mixed with impurities, found in strata of Cretaceous and other formations, and is forming at the present time along the margin of the continental shelf in the Atlantic Ocean and elsewhere. It promises to be an important source of potassium, in which the New Jersey deposits are especially rich. They also contain much phosphorus.

Metallic Aqueous Deposits

Manganese Ores. — Nodules of oxide of manganese occur in many parts of the deep sea in the region of red clay deposits (Fig. 174). They are more or less rounded or irregular masses of black color. Oölitic pyrolusite (MnO_2), an iron-black mineral of metallic luster, occurs interstratified with other beds in certain localities. A hydrous oxide of manganese (wad) occurs as an amorphous earthy deposit in bogs, generally associated with iron ores.

Limonite. — Bog iron ore, hydrous oxide of iron ($2\ Fe_2O_3 \cdot 3\ H_2O$). — This occurs in massive, botryoidal, earthy, or porous masses of yellow or ochery color and yellow streak. It forms deposits in bogs and swamps, in shallow water, in depths above 12 feet, from the oxidation of carbonate of iron carried into the bog in solution. The ores are always mixed with sand or earthy impurities. There are several other ferric hydrates, some with less and some with more water; *e.g.* Göthite ($Fe_2O_3 . 2\ H_2O$). Oölitic limonites occur in older strata, where they form an important source of iron, though of low percentage. Such

are the *minette* ores of Lorraine and Luxemburg, formerly one of the chief domestic sources of iron in Germany. These are believed by many to have resulted from the oxidation of oölitic siderite or glauconite.

Hematite. — Red oxide of iron (Fe_2O_3). — This ranges in color from deep red to reddish brown and black with red streak. It occurs interbedded with shales and limestones in the Palæozoic formations of Germany, France, Bohemia,

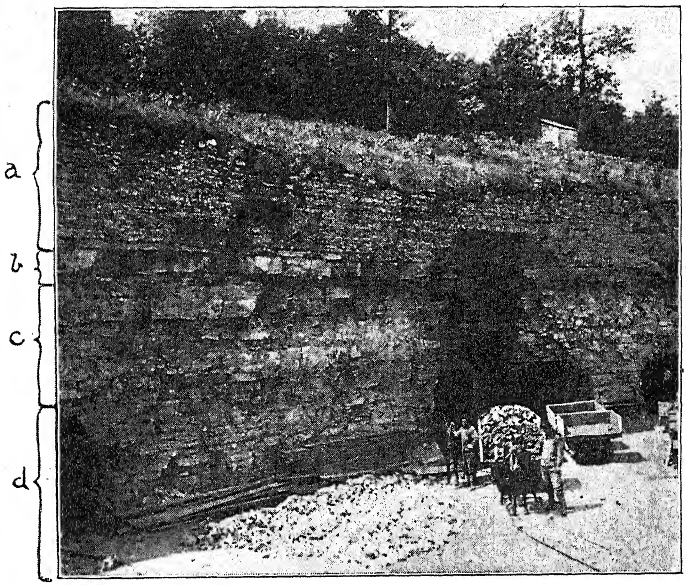


Fig. 163. — Quarry-wall of Cummings Cement Mine, Akron, Erie Co., N. Y. The upper bed (*a*) is a very cherty limestone (Corniferous) the chert nodules standing out in relief as the result of weathering; (*b*) Onondaga limestone without chert; (*c*) Akron dolomite, 7 feet thick, with fossils of upper Silurian Age. Between it and the Onondaga limestone (Middle Devonian) is a hiatus or break in succession involving the whole of the lower Devonian, which is absent. The two formations are disconformable; (*d*) Bertie water-lime mined for natural cement. (Courtesy N. Y. State Museum.)

and the United States, where the (Clinton) iron ores of New York and the Appalachian region form a characteristic example. Many of these beds appear to be replacement of limestone by the iron; in other cases the iron ore seems to be a primary deposit.

Siderite. — Carbonate of iron ($FeCO_3$). — This important iron ore occurs in crystallized form in veins cutting limestone and other rocks, and is readily recognized by its perfect rhombohedral cleavage, vitreous to pearly luster, greenish to brownish color, and translucent to subtranslucent character. It is more common, however, as an interbedded rock in the older sedimentary series,

being known as clay-iron-stone, spherosiderite, or black band. Clay-iron-stone has a dense or fine-grained structure, forming concretions, which often include

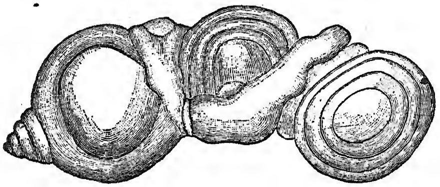


FIG. 164. — Clay-iron-stone concretion, Connecticut valley. (After Gratacap.)

organic remains (Fig. 164). The "black band" forms continuous layers in the formations which carry coal.

CHAPTER XI

MODE OF OCCURRENCE AND ORIGIN OF THE AQUEOUS OR HYDROGENIC ROCKS

Types of Deposits

Each of the several water bodies of the earth may form precipitates of mineral matter, and hence we may classify these deposits under the following heads:

A. *Marine* deposits, or those formed in the sea and its dependent water bodies.

B. *Lacustrine* deposits, or those formed in lakes, ponds, fresh-water marshes, salinas, playas, etc.

C. *Fluviatile* deposits, or those formed by rivers in their beds, or on the flood-plain or delta surfaces, except those formed in lakes along the river course, or at its mouth.

D. *Terrestrial* deposits, or those formed by springs and by the ground water in fissures, caverns, cavities in the rock, etc. To these belong many important deposits of mineral matter.

The several types may grade one into the other, but their main characteristics are quite distinct.

Sea-Water and the Evaporation Products and Chemical Precipitates Formed from It

Amount of Salt in Sea-Water. — As has been noted in the preceding chapter, the oceans, which are the large bodies of sea-water lying between the continents, contain the normal salt water, in which about 35 grams of salt occur in every liter of water. Since a liter of pure water weighs 1000 grams, the quantity of salt is essentially 35 per thousand by weight, which is expressed by the formula 35 per mille (or $35\frac{0}{00}$). This corresponds, of course, to 3.5 per hundred or 3.5 per cent (3.5%), but since the difference in salinity between different water bodies is often very slight, and

because in brackish and fresh waters the actual quantity of mineral matter in solution is very small, it is more satisfactory to express the quantity in permillages than in percentages.

The quantity of salt in solution determines the *salinity* of the water. Thus the average salinity of the ocean water is 35 per mille, (3.5 per cent), varying somewhat for the different oceans, for different parts of the same ocean, and for different depths. On the other hand, the salinity of the Red Sea surface waters is 38.8 per mille, while that of the surface waters of the Black Sea is only 18.3 per mille, which is due to the fact that this water body is almost entirely cut off from the rest of the sea, and that it receives many fresh-water rivers. Finally, the average surface salinity of the Baltic Sea is only 7.8 per mille, whereas if the water of this enclosed basin is taken as a whole, it is somewhat more saline because of the greater salinity of the deeper layers. Even then, however, it is only 10 per mille. The Baltic Sea, moreover, shows a remarkable gradation in the salinity of its waters from west to east. Where it joins the North Sea at the Skager Rack, the salinity is 34 per mille, but in the Kattegat it is only 22 per mille. Thence it gradually decreases eastward and northward until the waters near the heads of the Gulf of Finland and that of Bothnia are essentially fresh.

Composition of the Sea-Salts

Although, strictly speaking, the material held in solution by the water of the sea is not in combination as salts, such as are produced on evaporation, but rather in the form of ions, the basic elements and the acid radicals being separated, nevertheless it is customary and convenient to consider them as combined into the form of salts. Among these, common salt or sodium chloride makes up the bulk of the material, being nearly 78 per cent of the total mass of salt, or over 27 per mille of the salinity (which is taken as 35 in round numbers). In the following table the composition of the sea-water salts is given in the form of such combinations, together with the permillage of each in normal sea-water, and the number of short tons in a cubic mile of sea-water.

With the calcium carbonate are included the small quantities of other salts present, such as the iodine, lithium, manganese, and phosphorus salts, and the silver, gold, nickel, and other metals which are present in minute quantities in the solution.

TABLE OF THE COMPOSITION OF SEA-SALTS

Salt	Symbol	Percentage of Total Salts Taken as 100	Permillage or Actual Weight in Grams per Liter of Sea Water	Tons of 2000 Lbs. each per Cubic Mile of Sea Water
1. Sodium Chloride	$NaCl$	77.758	27.213	131,526,080
2. Magnesium Chloride	$MgCl_2$	10.878	3.807	18,399,360
3. Magnesium Sulphate	$MgSO_4$	4.737	1.658	8,012,480
4. Calcium Sulphate	$CaSO_4$	3.600	1.260	6,089,440
5. Potassium Sulphate	K_2SO_4	2.465	0.863	4,169,760
6. Calcium Carbonate	$CaCO_3$	0.345	0.123	583,520
7. Magnesium Bromide	$MgBr_2$	0.217	0.076	367,360
		100.000	35.000	169,148,000

Common Salts Produced by Evaporation of Sea-Water

The two principal salts which are produced by the evaporation of sea-water are the common salt, sodium chloride ($NaCl$), and gypsum or calcium sulphate, with two molecules of water ($CaSO_4 + 2\,H_2O$). By local oversaturation with lime, calcium carbonate ($CaCO_3$) may also separate out, but this is more commonly produced by chemical reaction. When the evaporation has gone very far, other salts, such as those of magnesium, and finally potash salts, separate out. Common salt and gypsum are obtained on many sea-coasts, either by evaporation of the water by artificial heat, or by conducting the sea-water into large shallow "pans," that is, fields surrounded with dams and having a hard, flat bottom. When the outlet of the pan is closed, evaporation takes place under the influence of the sun and drying winds, and after a while gypsum separates out. When most of this has been deposited, the water is conducted to another pan, where evaporation continues until a large part of the common salt (sodium chloride) has separated out. Then the remaining dense brine, which is called the *mother liquor*, is drawn off and either returned to the sea or further evaporated for the rarer salts. In this manner a large part of the world is supplied with its domestic requirements of salt, though vast quantities of this commodity are also obtained from inland salt deposits, which are the product of evaporation either of sea-water or of inland salt-bearing waters, in former geological periods.

Experiments in Evaporation of Sea-Water

In 1849, the Italian chemist, J. Usiglio, published the results of experiments which he had made at Cette on the south coast of France. He had taken 5 liters of the sea-water from the Mediterranean and evaporated this, keeping an exact record of the point which the evaporation had reached when separation of the several salts took place, and determining the amount of the various salts separated at the successive stages.

No separation of salts occurred until the water was evaporated to nearly one half its volume, when the iron oxide and a part of the carbonate of lime of the sea-water separated out. Later still, when the original 5 liters of the water had been reduced by evaporation to about one liter, the remainder of the carbonate of lime, together with the hydrous sulphate of lime, or *gypsum*, was precipitated. More than 84 per cent of the total amount of gypsum contained in the sea-water was deposited before the water became dense enough to allow separation of the common salt ($NaCl$), the remainder of the gypsum being thrown down with that salt and with various amounts of magnesium salts ($MgSO_4$ and $MgCl_2$), and finally with sodium bromide. A significant fact was that no sodium separated out until the evaporation had reduced the original 5 liters to less than half a liter, or to less than one tenth the original volume. At that time the amount of solid matter still held in solution in the half liter of water remaining was about 184.4 grams, which would correspond to 368.8 grams per liter, or a salinity of 368.8 per mille, whereas the salinity of the original sea-water was about 38.5 per mille.[1] From this we must conclude that a water body must reach this high degree of salinity by evaporation before salt can be deposited in nature. Since there are to-day no known large bodies of water with such a salinity, it follows that extensive salt deposition is not going on to-day by simple evaporation of large bodies of sea-water. To be sure, there are many small and shallow marginal lagoons on the sea-coast, and especially on the shores of more or less enclosed salt-water bodies, such as the Black and Caspian Seas, and Great Salt Lake, where evaporation goes far enough to precipitate salt — but this is, as a rule, only in comparatively small amounts, though commercially important.

Complete evaporation of the 5 liters of sea water was not achieved by Usiglio, for his experiments ceased when the volume had been reduced to about 81 cubic centimeters. This remaining dense "mother liquor" retained all of the potash salt of the original sea-water in solution, together with some of the sodium and magnesium salts. The amounts present were as follows:

$NaCl$		12.9425 grams
$MgSO_4$		9.2725 grams
$MgCl_2$		15.8200 grams
$NaBr$		1.6500 grams
KCl		2.6695 grams
	Total	42.3545 grams

[1] It is probable that actual separation of salt ($NaCl$) begins at a somewhat lower salinity, for at the stage here noted something over 3 grams of salt had already separated out.

This corresponds to a salinity of 522.9 grams per liter or 522.9 per mille (52.29 per cent).

The salts of the mother liquor are precipitated only at very high or very low temperatures, and from this we must conclude that potash deposits in nature are formed only under exceptional conditions.

Special Conditions Favoring Deposition of Sea-Salts

Modern Examples

From the foregoing it becomes apparent that the first requisite for the deposition of sea-salts in nature is the concentration of the sea-water under the influence of conditions which favor evaporation, such as the heat of the sun and, above all, drying winds. That such evaporation cannot go on in the open ocean is apparent, and so we must look to bodies of sea-water cut off from the main oceans.

The Caspian Sea (Fig. 165). — This, the largest isolated salt-water body of the earth, may in many respects be considered typical. It lies within the region of drying winds, and is partly surrounded by deserts. Evaporation has gone so far that its surface is 85 feet below sea-level, yet the salinity of its water is only 12.94 per mille, or a little over one third that of normal ocean water.[1] This is due to the fact that a large amount of fresh water is brought in by the Volga and other rivers tributary to it, so that in spite of the evaporation, the salt content is very low. As we shall see later, much of the original salt has been specially concentrated in the Kara Bugas Gulf and other dependent bodies, and some salt has no doubt been deposited on the bottom of the lake and then preserved by a covering layer of impervious material (gypsum, clay, etc.).

The Black Sea. — This nearly, but not quite, isolated mediterranean water body has a surface salinity of only 18.3 per mille, but the lower layers are denser, so that the average salinity of the water as a whole is 22.04 per mille. Obviously no salt can be deposited in the open parts of this sea.

There can be no question, however, that were it not for the supply of fresh water, both the Black and the Caspian seas would have a high salinity, while the Baltic would be nearer to sea-water in that respect. Indeed, should the fresh-water supply be entirely cut off from the Caspian, continued evaporation would result in the separation of most of its salt upon the bottom of its basin, and eventu-

[1] Average of five analyses made in 1878.

ally only a layer of mother liquor would remain to cover these deposits, and under special conditions this mother liquor might also be forced to part with its salts. That such evaporation of large

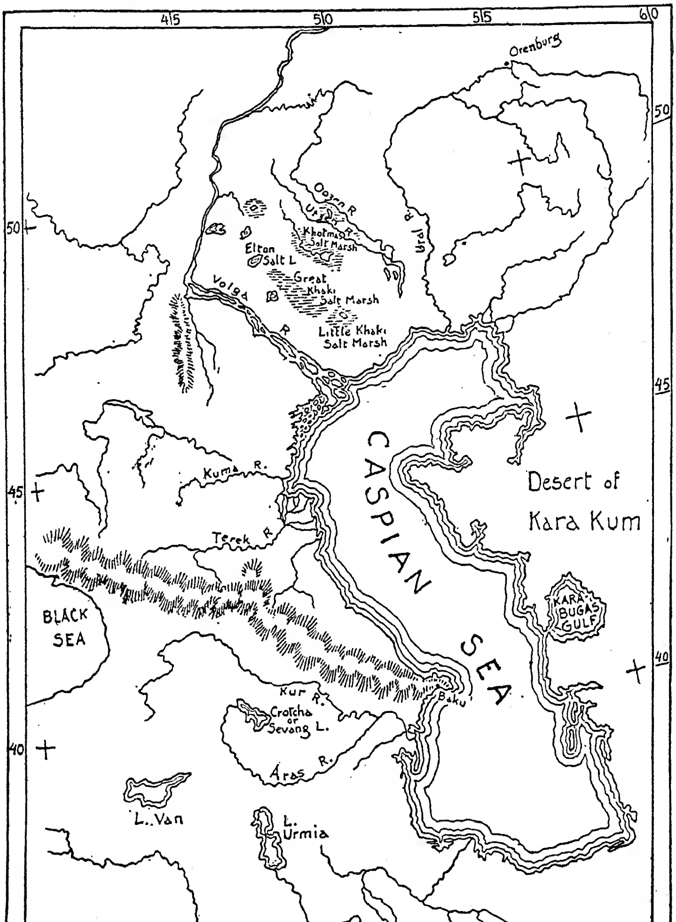


FIG. 165. — Map of the Caspian Sea and the salt lake region north of it.

enclosed bodies of sea-water has occurred in the past history of the earth is indicated by the nature of the salt deposits now found enclosed in the rocks of the earth's crust, as will be seen presently. To-day such deposits are formed in local "salt pans" along the

margin of the Black Sea, the Red Sea, and especially in the Ran of Cutch on the west coast of India, deposits which for centuries have supplied the natives with salt.

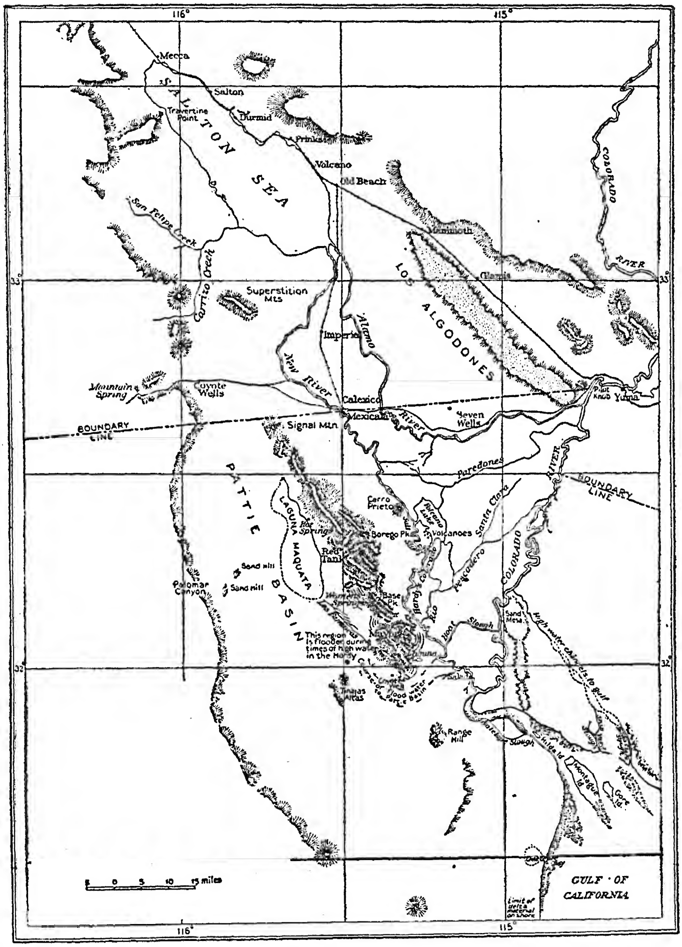


FIG. 166. — Map of the Colorado Desert with the Salton Sink and Pattie Basin. (After Sykes, from McDougal, Am. Geog. Soc. Bulletin.)

The Salton Sink (Fig. 166). — This is a great depression at the head of the Gulf of California, surrounded on three sides by high mountains which shut out the moisture-bearing winds, especially on the Pacific side. The valley is separated from the Gulf of Cali-

fornia by the delta of the Colorado River. The lowest part of its floor lies 273.5 feet below sea-level, and is occupied by a small lake, which is surrounded by extensive salt deposits. It is generally held that this depression was formerly a part of the Gulf of California and was cut off from it when the Colorado built its delta. Under the influence of the drying winds which descend from the Coast Ranges, the cut-off portion of the sea-water evaporated, and much of the salt was deposited on the floor of the basin, which was converted into a desert. Some of the salt may have been previously removed, when the Colorado drained into this basin and converted it into a fresh-water lake, which stood 40 feet or more above sea-level, as shown by old shore lines. Recently the Colorado has several times reëntered this basin and enlarged the central lake.

Effects of Condensation of Sea-Water on Its Animal Life

A moment's reflection will show that in the process of evaporation and concentration of the cut-off portion of the sea-water, all the animals which lived in that water would be killed, and their remains would sink to the bottom or be cast upon the shores. The shells of the Mollusca, the horny coverings of Crustacea, and the bones and teeth of fish and other vertebrates would be embedded in the layer upon which the salt later comes to lie. Thus a very definite and restricted fossiliferous substratum is produced for salt deposits of this type, and this will furnish a criterion by which ancient salt deposits can be interpreted. If the change in salinity is gradual, because the water body subject to evaporation is large, extensive fossiliferous deposits may be formed, including important beds of limestone, before the water is dense enough to kill the organisms. After that the water will remain essentially lifeless (though there are certain forms of animals which live only in strong brines), and the deposits formed in it will be barren of organic remains. An exception to this may, however, occur if the sea should break into the basin again, flooding it with normal sea-water, and bringing in with it the normal sea-fauna. Then, if the basin is again cut off from the sea, evaporation will set in with the repetition of the series of evaporation deposits.

Order of the Deposition of Sediments and Salts

If the basin whose waters become subject to evaporation is large, the waters, as they shrink, will leave a succession of de-

posits of various kinds around the margin. Along the shores would be found sands and clays which farther out might merge into organic limestone. As the sea-water becomes concentrated, the organically formed limestones would come to an end, and chemically formed limestones and dolomites would take their place. Gypsum or anhydrite deposits follow next, and finally, as the water becomes very saline and the area much contracted, salt is deposited. Last

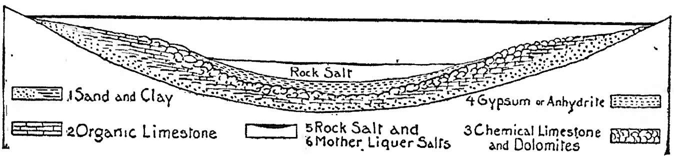


FIG. 167. — Diagrammatic cross-section of a cut-off basin, and the deposits formed in it after complete evaporation.

of all, the mother liquor salts are precipitated under favorable conditions, but only in the central area of the original basin, where the last of the water lingers. The relationships of these several deposits are shown in the preceding diagram (Fig. 167), which is entirely schematic. It must be emphasized that normal salt deposits formed from evaporating sea-water must always be underlain by a layer of gypsum or its anhydrous equivalent, the mineral anhydrite.

An Ancient Rock-Salt Deposit Formed by Evaporation of Sea-Water

Among the many salt deposits within the earth's crust which were formed during earlier geological periods and preserved through burial by later deposits, a certain number can best be explained as formed by the evaporation of cut-off portions of the sea in the manner above outlined. This means, of course, that they have the essential characteristics which we have seen are the normal accompaniments of salt deposits formed from complete evaporation of a cut-off body of sea-water. The most notable example is found in the great salt deposits of North Germany (Magdeburg-Halberstadt region), most widely known as the Stassfurt deposits, though this is only one of the localities where these salts are mined. Their peculiar interest lies in the fact that they have associated with them the rare potash salts which, we have seen, are precipitated

from the mother liquor on complete evaporation of the sea-water. Before the World War these deposits furnished by far the largest amount of potash to the commerce of the world, and their abundance is such that they can supply the entire world at the present rate of consumption for perhaps 2000 years to come.

If we take a section through these deposits from top to bottom, as revealed by the numerous boreholes and by mines in operation, we find the following characteristic succession:

At the base lies a variable thickness of limestones and dolomites, which in some sections contain old reefs formed by organisms which inhabited these waters while they were still connected with the sea, and for some time after. This limestone is known as the *Zechstein*, and it takes its definite place with the salt deposits and with the underlying red sandstones (Rothliegendes), in the series of successive formations which were made during the later portion of the Palæozoic era of the earth's history.

Above the Zechstein limestones and dolomites lies a formation of anhydrite and gypsum 100 meters in thickness, and this is followed by the salt beds. These average 245 meters in thickness and are subdivided by about 3000 layers of anhydrite, the so-called annual rings. Above this follow the mother liquor salts which have given these deposits their great value. They include more than 30 rare minerals, the more abundant, as a rule, in layers or strata, the whole averaging from about 60 to over 90 meters in thickness. The most important of them from a commercial point of view are, of course, the potash salts. Above these mother liquor salts occurs a second series, beginning generally with a salt clay containing remains of marine animals, followed by anhydrite (30–80 meters) and rock-salt, with about 400 annual rings of *polyhalite*, which is a complex hydrous sulphate of calcium, magnesium, and potash. The series is closed by a succession of minor layers of red clay, anhydrite, rock-salt (about 40 meters), anhydrite, and red clay, the last forming the top of the deposits. Throughout the entire series, except in the basal Zechstein limestones and the salt clay at the middle, remains of organisms are wanting, except a few plant fragments, which were blown into the water body. It appears then that both series of deposits, the lower as well as the upper, represent the succession which we have seen is characteristic of a progressively drying up cut-off portion of the sea. Moreover, as we shall see later, they differ from the succession of salt deposits formed in other ways, and they may, therefore, unhesitatingly be interpreted as accumulations of the first type. The regular intercalation of the anhydrite layers in the lower salt suggests that they are due to seasonal fluctuations in the density of the water — a periodic slight reduction in the salinity during a moister period putting a temporary end to salt deposition and permitting the formation of anhydrite, which is separated from less concentrated waters rich in salt. If these changes were of annual recurrence, as seems likely, it would appear that the formation of this salt mass took three thousand years. Each annual ring is on the average about 7 millimeters thick, while the salt layers with which they alternate are from 8 to 9 millimeters in thickness.

After the deposition of most of the mother liquor salts, a period of fluctua-

tion occurred, and salt with polyhalite layers was formed. This alternation, too, is probably seasonal, but shows that the brine was now more highly concentrated and of changed composition, and it is probable that regular changes in temperature were most influential in producing the succession of deposits. The higher anhydrite and salt series indicates that the sea-water again filled the basin, then it was cut off anew, and again underwent complete evaporation. It is also quite probable that the waters of these basins were enriched by salt brought in solution by intermittent streams from the surrounding hills, as is the case in many modern desert basins, and that, because of this excess of salt, anhydrite, rather than gypsum, was deposited.

We cannot, however, settle the question of origin from the deposits of North Germany alone. If they were formed by the drying up of an enclosed sea, there should be neighboring salts and sediments which should show such variations as we would expect nearer the shores of this water body, and these deposits should be of the same age. The method of searching out and determining formations of like geological age in different parts of the world will be dealt with later. Suffice it to say here that such age determination and correlation of formations in different countries is quite possible by the aid of fossils, by the relationship of the beds to one another, and by other criteria.

Taking, then, such deposits of the same age in other parts of Europe, we find first that the mother liquor salts fail as we proceed away from the North German region, where apparently was the center of concentration. Salt is still found in a number of sections even in eastern England. Here, however, magnesian limestones prevail, some of them showing a peculiar structure suggestive of chemical deposition (Fig. 160, p. 221). Limestone formed of a restricted number of organic remains elsewhere makes up the deposit of Permian age in England. Finally, in the north and west of England, only red sandstone deposits represent the Permian, these being formed near the old shore-line of the Permian basin, and in part above it, by rivers which brought sands from the uplands and dropped them in their lower shallow courses (Fig. 168).

In the other direction, toward the Ural Mountains of Russia, a change in the character of the Permian formations may also be observed. At first limestones predominate, but farther east these are largely replaced by sandy and clayey beds, among which coal seams are found, which indicate a swamp-land condition.

It seems practically demonstrated, then, that these ancient salt deposits with their valuable beds of potash salts were formed by

the drying up of a large body of sea-water which had become separated from the main ocean by the formation of a land barrier. This water body appears to have extended from central England on the west nearly to the Ural Mountains on the east. Its southern

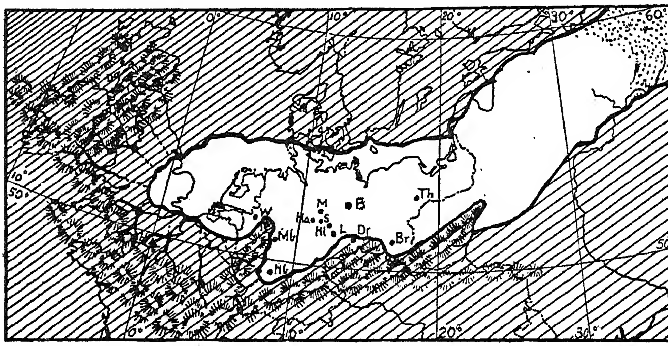


FIG. 168. — Map of the Zechstein Sea of Permian time in northern Europe, showing the approximate outline of that water body, and the mountains of that period. B=*Berlin;* Br.=*Breslau;* Dr.=*Dresden;* Ha.=*Halberstadt;* Hb.=*Heidelberg;* Hl=*Halle;* L=*Leipzig;* M=*Magdeburg;* Mb=*Marburg;* Th=*Thorn;* W=*Wesel.*

boundary was north of the Danube, and its northern in the region of the Baltic Sea of to-day. A significant corollary is that the climate of North Europe was very much dryer at that time than it is to-day, for at present no such complete evaporation would take place. This will be referred to again in a later part of this book.

DEPOSITS OF SALT BY CONCENTRATION IN LAGOONS. BAR THEORY OF OCHSENIUS

Complete evaporation of a salt lake is only one way — though a most effective way — of producing salt deposits. A second method consists in the concentration of the sea-water in a nearly shut-off lagoon in regions of arid climate. As a typical example of this we may select the Kara Bugas Gulf (Fig. 169), a bay which lies on the eastern coast of the Caspian Sea, from which it is separated only by a sand bar, across which a narrow strait maintains connection with the Caspian. On the other sides the gulf is surrounded by deserts, and there are no streams entering it. Since the Caspian Sea is a large salt-water body, though of lower salinity than the ocean, the Kara Bugas Gulf is nearly as satisfactory an illustration as a similar bay on the open sea would be.

Because of the narrow inlet from the Caspian, sufficient water is not supplied to counterbalance the evaporation over the surface of the Kara Bugas Lagoon, and so a slight difference of level is

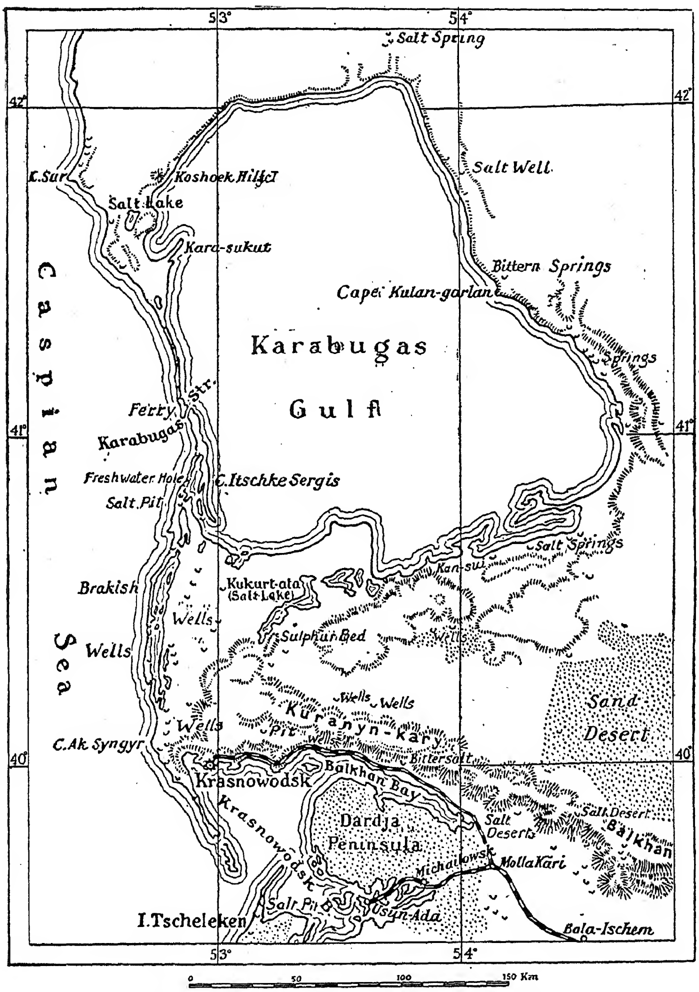


FIG. 169.—Map of the Kara Bugas (Karabugas) Gulf or *Adji-darja* (salt water), on the eastern border of the Caspian Sea.

produced, the Kara Bugas surface being sufficiently lower to cause a constant inflowing current of water from the Caspian (Fig. 169 *a*). Since the salt thus carried in solution is not removed, the waters of

the lagoon become more and more saline. A determination made some time ago showed a salinity of 285 per mille (28.5%), while that of the Caspian, from which the salt was abstracted, was only 12.94 per mille (1.294%).[1] This is a sufficient concentration for the deposition of some salts, but not of the common salt, which is not forming at the present time on the bottom of the gulf. An

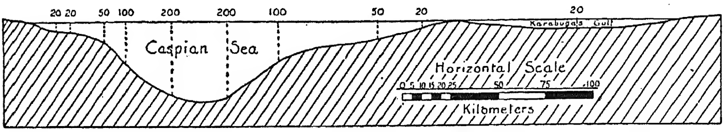


FIG. 169 *a.* — Cross-section of the Caspian Sea and the Kara Bugas Gulf, from Baku across the inlet to the northeastern shore of the Gulf. Vertical scale greatly enlarged. Depths given in meters. The level of the Kara Bugas is slightly lower than that of the Caspian.

extensive bed of sodium sulphate or glauber salt has, however, formed on the bottom of this bay, and much gypsum is being deposited.

It is evident that as concentration progresses, ordinary salt will be deposited, if, indeed, beds of salt do not actually underlie the layer of glauber salt, having been formed during a period of former greater concentration. It is also evident that so long as the connection with the Caspian is maintained, no mother liquor salts will be precipitated, since that requires nearly complete evaporation. It is not likely that such separation and complete evaporation of the Kara Bugas waters can take place so long as it remains separated from the Caspian by only a sand bar, for the lowering of the water in the Gulf would create a sufficient inward current to keep the inlet open, and even enlarge it. Therefore, while salt deposits of considerable thickness may accumulate on the bottom of such a gulf as the Kara Bugas, no potash salts can be formed in it.

The Caspian, like the ocean, abounds in animal life. Thousands of fish, many seals, and other animals are carried through the narrows across the bar and into the Kara Bugas, where they are killed by the high salinity of the water. Their carcasses float about and later sink to the bottom, or are cast upon the shore, portions of which are literally covered with dead fish which furnish food for migratory birds. Shells of dead mollusks, especially the cockle (*Cardium edule*), which lived in these waters before they became

[1] It must be remembered that the salinity of the ocean water is 35.0 per mille or 3.5%.

concentrated to their present degree, occur in enormous numbers on the shore of the Kara Bugas, and equally large numbers are buried with the fish remains in the mechanical sediments on the bottom of the gulf. These sediments are, therefore, highly fossiliferous, and should they harden into rock, they would constitute beds of fossiliferous clays and sandstones in close association with the salt deposits. Moreover, while salt deposits are forming in the Kara Bugas, normal sediments free from salts are forming in the Caspian in close juxtaposition to the Kara Bugas, and these, too, are fossiliferous. All of these factors must be kept in mind when we attempt to use this example, or others like it, in the interpretation of the history of older salt deposits.

From its simplicity this example has gained wide currency as an explanation of the origin of rock-salt deposits in all parts of the world. The theory was first developed, though not originated, by the German chemist, Professor Karl Ochsenius, and it is commonly spoken of as the "Bar Theory of Ochsenius." While it explains many an ancient salt deposit, especially the great series of Tertiary salts in the region of the present Carpathian Mountains and elsewhere, it does not satisfy the conditions found in other older salt deposits, especially those of the United States, for which another mode of origin must be postulated, as will be shown in a later section.

An Older Salt Deposit Formed According to the Bar Theory

Perhaps the best example of an older rock-salt deposit which can be explained by the Bar Theory was found in the salt beds of the Bitter Seas on the peninsula of Suez (Fig. 170). Before the Suez Canal was cut, these lakes were of very high salinity, and on the bottom of at least one of them an immense bed of rock-salt had formed. This has, however, been entirely redissolved by the fresher waters of the canal. A characteristic feature of this salt bed was not only the presence of many layers of gypsum, but also of innumerable layers of clay in which were embedded the shells of mollusks such as now live in the Red Sea near by, while similar shells were entombed in the sediments which formed on the bottom of the Red Sea during the period of salt deposition, though these sediments are free from salt.

We have here a deposit which satisfies all the requirements of the lagoon and bar example of the Kara Bugas, namely, a circumscribed area, presence of numerous organic remains in the salt-bearing series, and the association in a neighboring area (the Red

Sea) of normal deposits with the same fossils but with no salt. In the present case it is known that these Bitter Lakes formerly constituted an extension of the Gulf of Suez and the Red Sea, forming the ancient Heroöpolitan Gulf. The silting up of the mouth of this gulf, which was not yet complete during the sixth century before Christ, formed the bar which cut off the lagoon from the remainder of the gulf. According to some authorities, this bar appears to have been the site of the crossing of the Red Sea by the Israelites in their exodus from Egypt. With the formation of this bar, which now constitutes the southern margin of the isthmus of Suez, the conditions favorable to the deposition of the gypsum and salt were produced. Repeated overflow from the Red Sea supplied the waters and the mud in which were buried the organisms which could live here until the water became too salty. Then their shells and other remains sank to the bottom; a layer of gypsum was formed over them, and then a layer of salt, covered by a more or less impervious layer which prevented re-solution when next the waters of the Red Sea poured in again. In the waters thus freshened, new organisms developed from the larval stages brought by these waters, and a new cycle of deposition was inaugurated. The mother-liquor, however, never evaporated in this lagoon, but remained behind, forming the bitter waters of the lakes, which, however, have lost much of their character since the letting in of the sea-water by the canal.

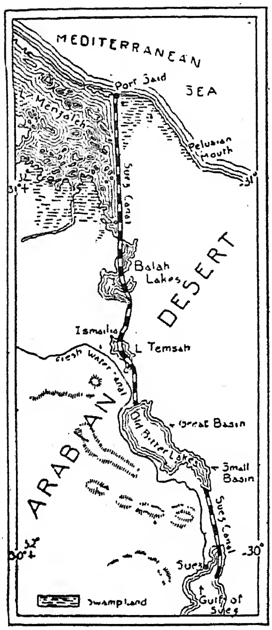


FIG. 170. — Map of the Bitter Lake of Suez and the Suez Canal.

DEPOSITION OF SALT IN INLAND DESERT BASINS

Salt deposits are forming in many portions of the world to-day, where no direct connection with the sea exists. The inland salt lakes and salinas are in some cases shrunken bodies of fresh water formerly of greater extent. This is the history of Great Salt Lake

of Utah, which is only a remnant of a much larger fresh-water lake — Lake Bonneville. By evaporation and concentration of the water in the deeper part of the basin, the salinity was increased, and finally in some cases reached the concentration necessary for the deposition of salt. Much additional salt is constantly brought into the lake by the streams which feed it. Naturally the question as to the origin of the salt in these waters arises. The answer is that it is leached out of the rocks within the drainage area of the basin. Not all rocks contain sodium chloride, but this is generally present in clastic and other rocks which have been formed on the bottom of the sea in former geological periods. These rocks include ancient sea-water, often highly concentrated, within their pores, where it is hermetically sealed up and is set free only when the rocks are subsequently exposed to atmospheric decay and erosion. Then the *connate water*, as it is called, evaporates, but the salt remains behind to be redissolved by the surface waters and carried away. If it is carried into an inland drainage basin from which there is no escape, except by evaporation, salinas and even extensive salt deposits are formed. Such areas, covered with glistening white rock-salt or with irregular salt masses, are found in the desert basins of central Asia (Figs. 171 *a*, *b*), and indeed are not uncommon in many other desert areas. So long as the supply of salt lasts, such a deposit will continue to grow by periodic additions, and thus beds of salt of great thickness may form. If silt is brought in during a period of flooding, or if sand or dust is blown across the salt plain, a layer of clastic sediment may form over the salt, and this in turn may again be covered by pure salt deposits. As a rule, however, gypsum is not deposited in such basins, not because the connate waters imprisoned in the rock did not contain it, but because after it is set free it is less readily redissolved by the surface waters than

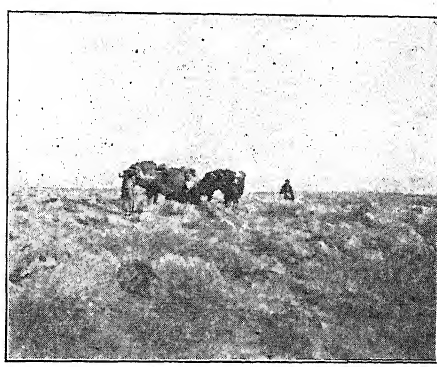


FIG. 171 *a*. — The irregular salt surface of the Salt Plain of Lop, Eastern Turkestan. (After a photograph by Ellsworth Huntington.)

is the common salt, and that which is dissolved is likely to separate out again from the waters before they reach the central basin. In conformity with this we often find the sands which surround such basins filled with gypsum crystals which have grown from the ground water as it passed through the sands, carrying the more soluble sodium chloride to the central basin.

FIG. 171 *b*. — The southern edge of the Salt Plain of Lop, in Turkestan. (From a photograph by Ellsworth Huntington.)

In like manner the potash salts will not, as a rule, reach the central basin, for though they are very soluble, the fine particles of the soil of the desert among which the water must find its way to the central basin have a great affinity for the potash and will, by some still little understood process, separate this substance from the water during its passage. Hence the water which reaches the central basin will contain little else than pure sodium chloride, and therefore only

FIG. 172. — Silver Peak Marsh, Nevada, a typical playa (Photo F. R. Porter from U. S. G. S.).

pure rock-salt deposits are formed. Gypsum may, however, result from the alteration of limestones formed of lime-mud and dust which is washed or blown over the salt. In this manner gypsum beds may be formed above the salt beds, whereas in normal marine deposits of salt, or in those due to the evaporation of cut-

offs, the gypsum will underlie the salt. The importance of these facts in the determination of the origin of older salt beds is very great. Another fact that must not be overlooked in desert salt deposits is that the parting and enclosing layers of sediment will contain no marine organisms. They will, indeed, be for the most part entirely free from organic remains. A few desert organisms and migratory birds may, however, become entombed in these deposits or even in the salt itself, but their terrestrial character is readily recognized by the expert. Huntington reports finding, in the salt of Lop Nor in eastern Turkestan, a dead plover which had been preserved in the salt for centuries. Around the border of some of the Persian salinas a zone of mud is sometimes found, in which are entombed the bones of animals which came to drink of the salty water and perished there.

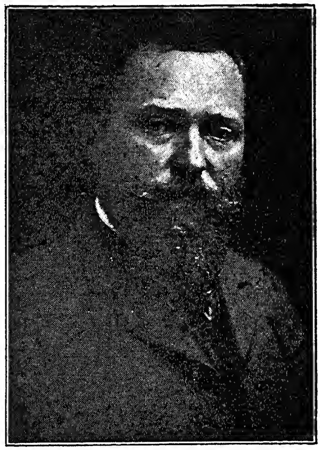


FIG. 173.—Professor Johannes Walther, widely known for his investigations of desert phenomena.

Beyond these salinas in all directions we pass into the region of desert sands and dust deposits, and these have very definite characteristics which can be recognized even after they have hardened into rock beneath a cover of other deposits. Thus the geologist will generally be able to recognize in the rocks associated with the ancient desert salts the structures which clearly indicate that origin. The appearance of a typical American salt-marsh or playa is shown in Fig. 172.

Among the geologists who have made extensive investigations into the origin and mode of deposition of desert salts, the foremost rank must be assigned to Professor Johannes Walther of the University of Halle. (Portrait, Fig. 173.)

An Ancient Example of a Desert Salt Deposit

In the central part of the state of New York, in western Ontario, and in southern Michigan, occur ancient rock salt deposits, all of which were formerly and some of which are still buried under thou-

sands of feet of rock, a considerable portion of the latter being of marine origin. The rock-salts themselves, however, which rest in some places upon marine beds of Lower Silurian (Niagaran) age and in others upon non-marine sediments, are in some places covered by marine beds of Upper Silurian age (Monroan) and are associated laterally with deposits of clastic material which shows all of the features of sediments found in modern deserts. Moreover, no fossils are found in these deposits nor in those which separate the several salt beds of the series from one another, nor are there any Middle Silurian beds of marine origin to be found within hundreds of miles of the salt deposits. Thus it appears that these very ancient salt beds of Middle Silurian age were formed in a desert which then occupied much of the area now covered by the Great Lakes and adjoining territory (see further, Chapter XXXIV).

No potash deposits are found associated with these salts, and from what he has learned so far, the student will realize that there is little likelihood of the finding of these salts unless it can be shown that the basal salt beds of some sections are not of desert but of marine origin, resulting from the drying up of the last remnant of the Niagaran sea which preceded the desert period.

There is, however, one important fact which seems to argue against such a marine interpretation of the basal beds, and that is the absence of gypsum or anhydrite beds beneath the salt. Indeed, the entire series of Salina salt deposits lacks the foundation layers of gypsum or anhydrite, though gypsum overlies the salt in a number of localities. Much of this is, however, known to have been produced by the alteration of former limestone beds which were invaded by sulphur-bearing waters.

Carbonate of Lime Deposits

Although some carbonate of lime separates out on evaporation of the sea-water, this is of such small amount that it practically disappears in the evaporation series produced along the seacoast and from cut-off bodies. Nevertheless, carbonate of lime deposits are formed in the sea, not so much by evaporation, — though such an origin may be ascribed to some deposits, — as by the force of attraction of other particles of lime in sea-water saturated with lime carbonate, or by the abstraction of the solvent carbon dioxide through agitation of the water. Chemical precipitation

of lime also takes place and is perhaps the most common mode of lime deposition in some places aside from that due to organic action. This precipitation, however, is due largely to the formation of ammonium carbonate by the decay of organic matter, and this ammonium carbonate reacts with the lime sulphate or other lime salts in the sea-water, producing calcium carbonate, which is precipitated, and an ammonium salt which remains in solution. The reactions may be written in the following way:

$$\underset{\text{Calcium Sulphate}}{CaSO_4} + \underset{\text{Ammonium Carbonate}}{(NH_4)_2CO_3} = \underset{\text{Calcium Carbonate}}{CaCO_3} + \underset{\text{Ammonium Sulphate}}{(NH_4)_2SO_4}$$

Or again

$$\underset{\text{Calcium Chloride}}{CaCl_2} + \underset{\text{Ammonium Carbonate}}{(NH_4)_2CO_3} = \underset{\text{Calcium Carbonate}}{CaCO_3} + \underset{\text{Ammonium Chloride}}{2\,NH_4Cl}$$

Where lime is precipitated by such reactions, it often forms more or less spherical or irregular masses or nodules, to which the name *concretions* is applied. Such concretions have been dredged from many portions of the sea, and they appear to be especially common where organic matter which has reached the floor of the ocean undergoes a process of decay. Such areas are, however, not universal because the organic matter on the ocean bottom is generally devoured by bottom-feeding animals before the decay progresses far. It is only where the character of the water, or the temperature, is such that bottom-feeders are scarce or absent, that decay of stray organic matter can take place.

Deposition of lime due to the attraction of other lime particles is illustrated by the hardening on the ocean bottom of the loose lime-sands and muds worn from the coral and other organic limestone masses in the sea. It is a general fact that wherever lime-mud, or sand, forms upon the sea-floor, this is soon bound together by the filling in, between the particles, of lime derived from the sea-water. This seems to take place most actively in warm regions, where the amount of lime in the sea-water is above the average. As a result, the floor of the ocean in such regions is a hard surface to which various stationary marine animals attach themselves, while others, such as certain worms or sponges, bore into this rock to a certain depth.

On the surface of ancient limestone beds we often find the marks of animals which had become cemented to it. Such cemen-

tation could of course take place only if the surface were of sufficient firmness, and this indicates that the old deposits of lime-sand, or mud, from which these beds were formed in the sea, hardened by further separation of lime, so that the animals living there could become attached to it.

Another illustration of such lime deposition is seen in the coating of lime around grains of quartz, basalt, or other sand, or around fragments of shell, etc., which are found on the shores of the Island of Gran Canaria in the Canary Islands. These coated grains are more or less spherical and of the texture called *oölitic* (see p. 217). By further deposition of lime between the grains they are bound together into a solid rock, an oölite, which is quarried at low tide. The water here is warm, having throughout much of the year a temperature above 20° C., and there is much lime in solution. Still another interesting example of lime deposition is seen in certain Mexican lagoons where insect eggs are coated with lime, producing a series of rounded oölite grains. Most of the grains of oölitic character are, however, produced by the activities of bacteria or minute algæ in the sea, and on this account must be classified as of organic origin. They will be more fully discussed in a later chapter.

Other Chemical Deposits in the Sea

Small quantities of other substances are deposited in the sea as the result of certain chemical reactions, or through attraction by material of like composition. The most important of these are phosphatic concretions and concretions of oxide of manganese, both of which have a wide distribution over the sea-bottom. A third group of such deposits forms grains of the green mineral glauconite, of which "green-sands" are made.

Phosphate of Lime. — This is produced by many marine animals which take the phosphoric acid either directly from the sea-water, or from their food. The phosphate of lime is built into certain hard tissues, as the shells of some brachiopoda (Lingula), the bones and teeth of fish, etc., and it is also present in the excrements of fish and other animals. Such particles accumulating on the sea-bottom have the power of attracting to them more phosphate and precipitating it upon their surfaces, which thus become a nucleus around which phosphate concretions are built. Such phosphate concretions are found on the ocean floor in many localities at moderate depths. They are also found in many old limestones, in which they are generally scattered. By the weathering of this limestone the nodules which are left behind are concentrated into beds which are rich enough to be worked. By solution of the

phosphate and by redeposition in veins or on the walls of cavities, or by replacing limestones upon which they rest, rich deposits of phosphate are produced.

Manganese Concretions. — Concretions of oxide of manganese with oxide of iron, clay, and other substances are also found on the floor of the deep sea in many localities (Fig. 174). The manganese and iron form concentric layers about some nucleus, which may be the tooth of a shark, or some other substance. It is not fully known whether the manganese is derived from the sea-water in which it is present in very small quantities, or whether it is derived from the decomposition of basic volcanic rocks on the floor of the ocean. Manganese concretions are also found in ancient marine deposits, and in some cases at least may represent concentration of scattered nodules by the weathering of the rock which contained them.

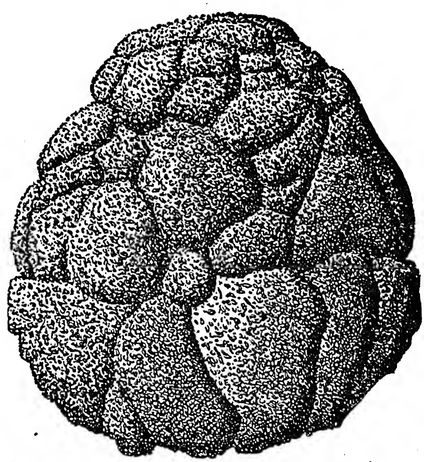


Fig. 174. — Nodule of oxide of manganese from Red Clay of abyssal ocean bottom. (After J. Murray.)

Glauconite. — Still another deposit formed by chemical means on the sea-floor, is the mineral glauconite, which, when abundant, forms beds chiefly composed of small grains of this mineral. On account of their green color such beds of glauconite grains are commonly called "green-sands." Chemically the mineral is an impure hydrous silicate of iron and potassium, and it is commonly formed from fine mud which fills the interior of small shells of Foraminifera (Fig. 196, p. 275), partly by the reaction with the products of decay of the organic matter in these shells, and partly by reaction with the substances in the sea-water. The whole process is too complex to be further discussed here, and should be taken up again in a more advanced course.[1]

[1] See A. W. Grabau, *Principles of Stratigraphy*, pp. 670–673, and the literature there cited.

Beds of green-sands are not uncommon in older marine and other deposits. The most characteristic examples are found in the strata of Cretaceous age which crop out in New Jersey and Maryland. Sometimes by exposure the iron of the green-sand is changed to an oxide, and ochery or red beds will be produced. Such is the vividly red sand bed which is so prominent in the section at Atlantic Highlands, N. J., and which underlies the town of Red Bank, to which it has given the name. Beds of green-sands are also common in the Cretaceous strata of southern England, where they are generally spoken of as the Green Sands. They also occur in France and elsewhere. Some beds of green-sands are, however, found in deposits which accumulated elsewhere than on the sea-floor.

Chemical Deposits and Evaporation Products of Lakes

Lacustrine Deposits

Lakes may be classed as fresh-water, alkaline-water, salt-water, and brine lakes. The salt-water and brine lakes have already been referred to, and it has been shown that the deposits in these are mainly pure salt (sodium chloride), and in some of the larger ones, like Great Salt Lake, also sodium sulphate or mirabilite. The Caspian must be differentiated from salt lakes of smaller size, as it is more properly a portion of the sea which has been cut off. Hence the deposits there are generally like those formed on the sea-coast.

Composition of Lake Water

The composition of lake water varies of course in an almost endless manner, no two lakes having water of exactly the same composition. Nevertheless, it is possible to select certain types or averages of groups, which represent in a general way the mineral substances present in such waters. Fresh-water lakes are of course the most abundant, and as their composition varies to a less degree than that of the other lakes, it is possible to give a general average. This is shown in the first column of the annexed table, in which the average also includes that of river waters, which are not essentially different from those of lakes. In the other columns the composition of a typical alkaline water (Owen's Lake, California), saline water (Lake Corongamite, Victoria, Australia), and brine (Dead Sea at 200 meters depth) are given, and the composition of ocean water is again given for comparison. In this table the composition is expressed in terms of *ions* rather than of salts, which is the more accurate way of statement.

TABLE OF THE COMPOSITION OF LAKE WATERS

NAME OF ION	SYMBOL	FRESH WATER	ALKALINE WATER	SALINE WATER	BRINE	OCEAN WATER
		Average Salinity 0.175 per mille	Salinity 213.7 per mille	Salinity 46 per mille	Salinity 251.1 per mille	Average Salinity 35 per mille
Carbonic oxide	CO_3	35.15	24.55	—	Trace	0.207
Sulphuric oxide	SO_4	12.14	9.93	1.65	0.22	7.692
Phosphoric oxide	PO_4	—	0.11	—	—	Trace
Boron oxide	B_4O_7	—	0.14	—	—	Trace
Chlorine	Cl	5.68	24.82	59.32	67.84	55.292
Bromine	Br	—	—	0.22	1.75	0.188
Nitrogen oxide	NO_3	0.90	0.45	—	—	—
Lithium	Li	—	0.03	—	—	Trace
Calcium	Ca	19.00	0.02	0.13	1.68	1.197
Magnesium	Mg	3.41	0.01	2.77	16.72	3.725
Sodium	Na	5.79	38.09	35.07	10.00	30.593
Potassium	K	2.12	1.62	0.84	1.79	1.106
Iron oxide / Aluminum oxide	Fe_2O_3 / Al_2O_3	2.75	0.04	—	—	Trace
Silica	SiO_2	11.67	0.14	—	Trace	Trace
Arsenic oxide	As_2O_3	—	0.05	—	—	Trace
		100.00	100.00	100.00		100.00

Deposits of Fresh-Water Lakes

The three most important types of deposits formed from the waters of fresh-water lakes and ponds are those of carbonate of lime and carbonate and oxide of iron.

Carbonate of Lime. — This is by far the most important constituent of lake waters, and for that matter, of fresh-water bodies of all kinds. Nevertheless, the actual quantity is smaller in fresh than in sea-water. As will be seen from the analysis a cubic mile of fresh-water contains on the average only 360,915 short tons of calcium carbonate ($CaCO_3$), whereas a cubic mile of sea-water contains 583,520 short tons of this mineral in solution. It must be remembered, however, that sea-water contains a vastly larger quantity of other substances, of which common salt forms 131,526,000 tons, while in average fresh-water it forms only about 19,656 short tons per cubic mile. Moreover, the total quantity of mineral substances dissolved in the sea is 169,148,000 short tons per cubic mile, in fresh-water only 854,100 short tons; that is, the sea contains about 200 times as

much mineral matter in solution. The mineral matter of fresh-water bodies is precipitated by three methods: evaporation, chemical reaction, and organic secretion. The last belongs to the topic of organic deposits.

Evaporation. — Lake waters are, as a rule, very far from being saturated with carbonate of lime, and for this reason such a substance will not be deposited as an evaporation product until much or all of the lake water is evaporated. An exception to this is the deposition of carbonate of lime in the form of calcareous tufa in the marginal pools or on beaches of great fresh-water lakes situated in dry climates, but constantly supplied with water by a large river. Such tufa forms by local complete evaporation of the water which lies in shallow marginal pools above the ordinary water-level and is replenished at intervals by spray and the waves. The spray which saturates the sands of the beaches may also, on rapid evaporation, leave behind carbonate of lime to bind the sand grains together. Such deposits of calcareous tufa are found in the old lake beaches on the slopes of the Colorado or Salton desert up to 40 feet above sea-level. These were formed when the Colorado River drained into the basin and kept it full of water up to that level, in spite of the rapid evaporation which was taking place in the dry climate of the region, and which has completely dried

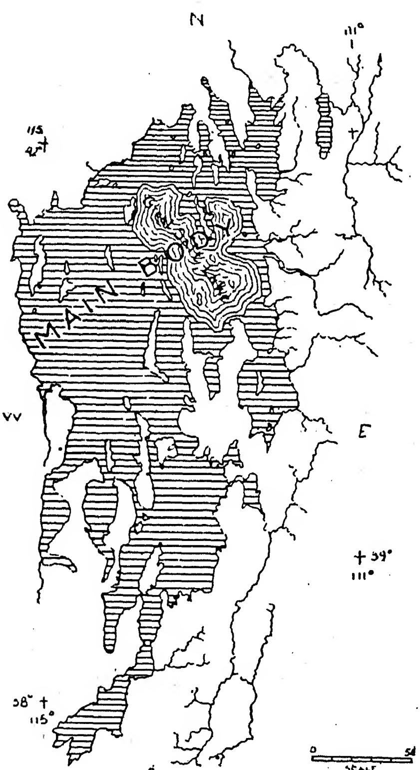


FIG. 175. — Map of Lake Bonneville and its present remnant, Great Salt Lake of Utah.

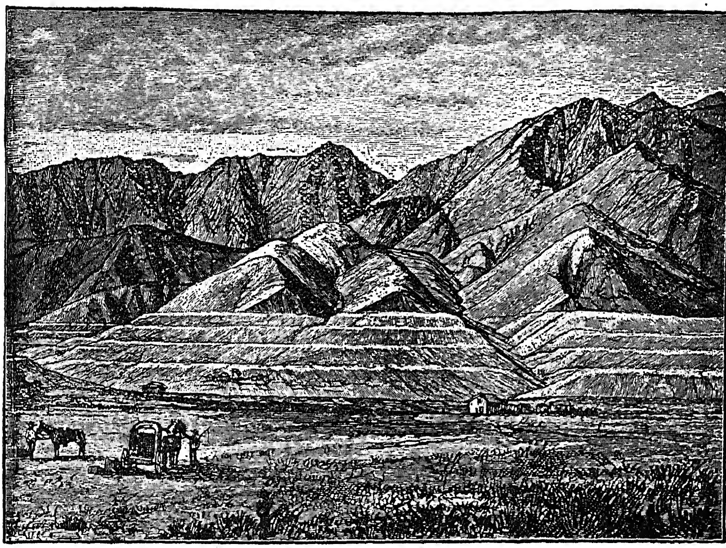


FIG. 176. — Terraces and shore-lines of Lake Bonneville, near Wellsville, Utah, showing contrast between littoral and subaërial topography. (After Gilbert.)

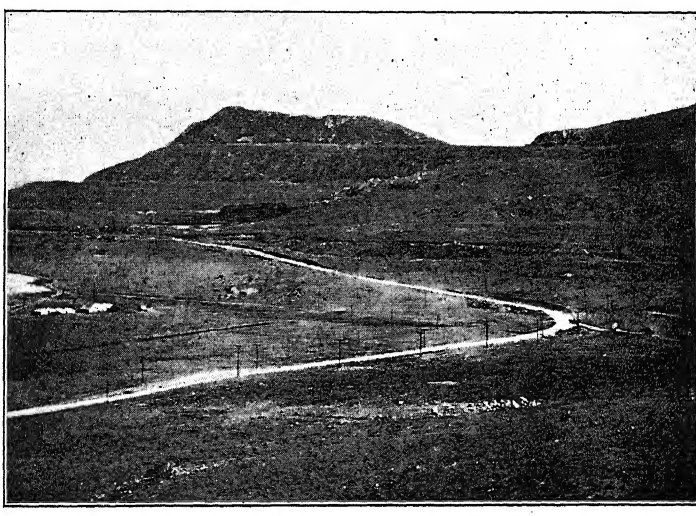


FIG. 177. — Abandoned shore-lines of Lake Bonneville. North end of Oquirrh Mountains, Utah. (Photo by F. J. Pack.)

out that basin since the Colorado has become diverted to the Gulf of California. The nearly complete evaporation of lake water is illustrated by the history of lakes Bonneville and Lahonton, which in an earlier period of the earth's history occupied large

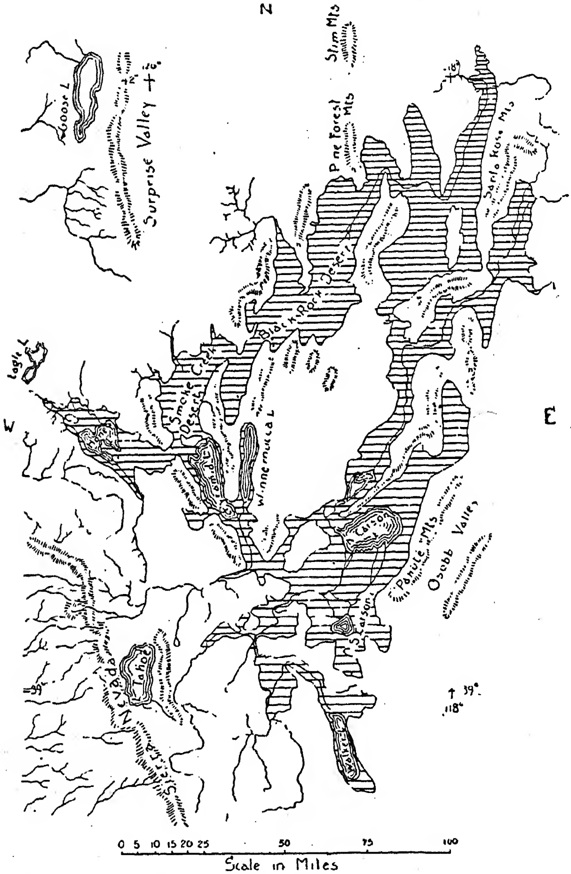


FIG. 178. — Map of ancient Lake Lahonton and some of the present residual water bodies.

areas in the western United States (Figs. 175, 178), and the old shore lines of which are still traceable (Figs. 176, 177). The product of evaporation of the water of these lakes was chiefly carbonate of lime in the form of calcareous tufa, of which several types were formed. This covers the older rock surfaces over wide areas (Fig. 176) and forms layers of tufaceous limestone, alternating with

deposits of sands and gravels, which it sometimes cements. In places these deposits form a mass over 50 feet in thickness, though elsewhere they are represented only by an average thickness of 20 to 25 feet.

Three types of calcareous tufa are found within the basin of old Lake Lahonton, each type belonging to a separate period of formation. The first and oldest is called a *lithoidal tufa* because it is rock-like, cementing the old gravels of the

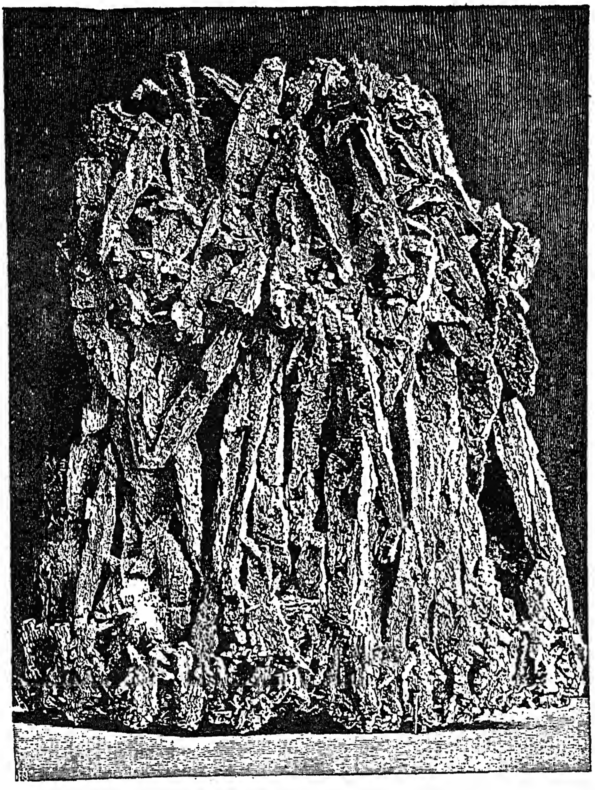


FIG. 179. — Thinolithic tufa or Thinolite, from Lake Lahonton Basin. (After Russell.)

lake floor, and it not infrequently contains shells of fresh-water Mollusca. The next type, formed after an interval of exposure, is known as *thinolithic tufa* (Fig. 179), and consists of a series of large prismatic crystals six to eight inches long and almost half an inch in thickness. These form a layer from six to eight feet thick where best developed. The final type of tufa is called *dendritic* (Figs. 159, 180), from its branching structure, and this is the most abundant,

covering the old rocks of the lake with a deposit from twenty to fifty feet thick. Sometimes this formed dome-shaped or mushroom-like masses up to five or six feet in diameter (Fig. 159, p. 219), and where these are crowded they often assume a polygonal outline resembling paving blocks. Internally these masses have a more or less radiate structure.

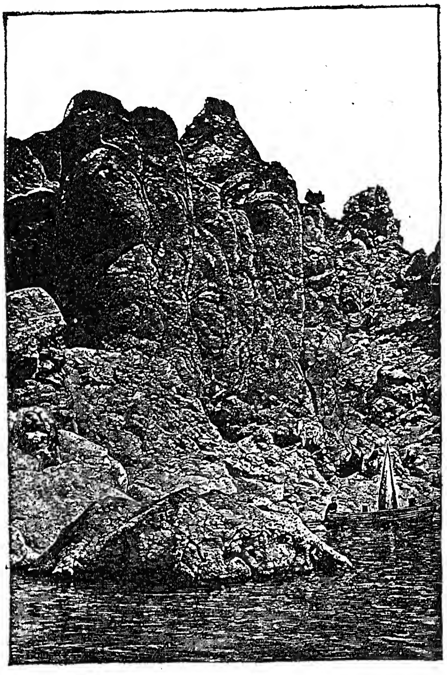


FIG. 180. — Tufa-domes, shore of Pyramid Lake, a remnant of Lake Lahonton. Dendritic tufa. (After Russell.)

Significance of lime deposits of this type. — Limestones like the above, due to evaporation, indicate a dry climate during the period of their formation. If such limestones are covered by other deposits, which later harden to rocks, they will form a member of a series of stratified rocks similar in general appearance to many that are found in the older parts of the earth's crust. If in such an older series the limestone member can be determined by its peculiar characteristics to have originated as an evaporation product of an old lake basin, a definite conception of the physical conditions of that region at the time of the formation of the limestone bed is gained. It is therefore important that the particular characteristics of such limestone beds should be understood. At the same time it must be remembered that with the passage of time, such a limestone will undergo more or less change, so that the old characters are to a greater or less degree obliterated or altered. Nevertheless, enough may remain to indicate the origin of the limestone, and from the adjoining formations and those lying beneath and above it additional evidence for or against the evaporational origin of such a limestone may be obtained. What may prove to be an example of this type formed in a past geological period (Permian), is the bed of Magnesian Limestone exposed on and near the coast of Durham in England, which shows a structure not unlike the spherical structure of the dendritic tufa of Lake Lahonton (Fig. 160, p. 221). The internal structure is, however, more strongly crystalline, which may be due to its greater age. (Fig. 18, p. 34.)

Chemical precipitation. — This will take place in stagnant lakes and ponds, the waters of which contain much carbonate of lime in

solution, and which moreover contain decaying organic matter. This decay, as in the ocean, will produce ammonium carbonate, which will tend toward precipitating the lime. It may be doubted, however, that much lime is precipitated in this manner from fresh water, since the presence of carbon dioxide, which is also formed as the product of decay, would tend to keep the lime in solution.

Organic separation. — The most common method of abstraction of lime from fresh water is that by the activities of organisms, both animal and plant. But deposits so formed belong to the group of organic rocks, and their discussion will be deferred to another chapter.

Iron Carbonate and Oxides. — Stagnant swamps are often covered by an iridescent film, which is the result of the oxidation, on contact with the atmosphere, of iron salts which were contained in the water. Such iron salts are originally in the form of ferrous carbonate ($FeCO_3$), which in mineral form is the ore *siderite.* This iron carbonate is derived from iron salts in the soil and has resulted from the decomposition of iron-bearing rocks (the ferro-magnesian silicates of igneous rocks), the leaching being performed by rain and ground waters which have taken up carbon dioxide (CO_2) from decaying vegetation. When such a solution of iron carbonate is brought into a lake or swamp, one of two things will happen. When there is much decaying organic matter in the swamp, this will appropriate all the available oxygen, and then the iron is deposited in the form of the carbonate. This is generally impure, being mixed with the mud held in suspension and carried down with the iron carbonate. This mixture is most frequently deposited around some object which forms the nucleus of an *iron-stone concretion,* as such structures are called (Fig. 181). Such iron-stone or siderite concretions when sufficiently pure form ores of iron, and they are commonly found in formations in which coal (the product of the partial decay of the vegetation) is also found.

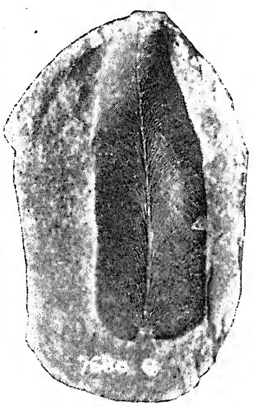


FIG. 181.— Clay-iron-stone concretion split in two, showing the impression of a fossil fern (*Neuropteris*). Mazon Creek, Ill. (Photo by B. Hubbard. Specimen in Columbia University.)

If, however, vegetation is not abundant, the carbonate will be changed to the oxide, by contact with the air and with the oxygen dissolved in the water, and in such cases an iron oxide will be deposited. This is commonly in the form of limonite, the yellow iron ore, in which water is present, and the loose, porous masses of this mineral which form on the bottom of such ponds are called bog-iron-ore. Such bog-ores are generally most abundant near the margins of the ponds and swamps and are often wanting near their centers. Sometimes such bog-ore forms very rapidly, some Swedish lakes having deposited layers several inches thick in twenty-six years.

The decomposition of the iron carbonate in the solution and its oxidation to insoluble iron oxide is aided by, and in some cases largely due to, the work of minute organisms in the water, the so-called "iron bacteria." Such deposits might be referred to the organic group, were it not for the difficulty of distinguishing them from purely chemical deposits such as those described.

Alkaline Lakes and Their Deposits

Under this heading are classed lakes in which carbonate of soda plays a more important part than carbonate of lime, which is generally present in small quantities only. The relatively great preponderance of the CO_2 radical, and the much reduced chlorine content, further differentiate typical alkaline lake waters from those of saline lakes, in which sodium chloride is the dominant salt in solution and the carbonates are insignificant in quantity. Sulphates and chlorides, however, are generally present, and one or the other or both may be abundant, making complex alkaline waters. In some cases, too, potassium may be an important element, exceeding even the sodium, as in Albert Lake, Oregon.

Some of the principal water bodies in which deposits of this and similar types are formed are:

Sodium Sulphate.—Laramie Lakes, Wyoming
Soda Lake, Cal.
Sevier Lake, Utah
Mono Lake, Cal.
Owen's Lake, Cal.
Searle's Lake or Marsh, Cal.
Albert Lake, Oregon
Altai and Domoshakovo Lakes, Russia

Sodium Carbonate. — Soda Lake, etc., Nev.
Owen's Lake, Cal.
Searle's Lake, Cal.
Natron Lakes, Egypt
Lakes in Hungary, Armenia, Venezuela, etc.
Borax. — Searle's Lake, Cal.
Death Valley, Cal.
Soda Niter (Chile Saltpeter). — Desert Lakes of Chile
Searle's Lake.
Potassium Nitrate (Saltpeter). — Cochabamba, Bolivia

Different salts may be deposited at different times by these lakes. Thus Searle's Lake or Marsh deposits both carbonate and sulphate of sodium and borax and niter as well. From Owen's Lake, California, both carbonate and sulphate of sodium are obtained. Common salt (sodium chloride) is also an accompaniment of the deposits in many of these lakes.

The greatest deposits of niter known in the world are found in the Atacama and Tarapaca deserts of Chile. The amount has been estimated at 254,760,000 tons and is found at elevations exceeding 2000 feet above the sea and from 50 to 100 miles from the coast. The crude sodium nitrate is known as *caliche* and is associated with anhydrite, gypsum, epsomite, halite, and other minerals. The origin of these and of the potash nitrates of Bolivia is not fully understood, but they were deposited from solution in drying basins.[1]

Deposits of Saline Lakes and Brines

These lakes deposit chiefly sodium chloride or common salt, especially those in which the waters are a brine, as is the case in most inland salt lakes. Great Salt Lake, Utah, the Dead Sea, and numerous Russian and Siberian lakes serve as examples. They supply vast quantities of common salt for domestic and other purposes.

Chemical Deposits and Evaporation Products of Rivers

(Fluviatile Chemical Deposits)

These are of comparatively rare occurrence and are confined chiefly to regions of arid climate. As carbonate of lime is the

[1] For fuller discussion, see A. W. Grabau, *Geology of the Non-metallic Mineral Deposits*, etc. Vol. I, Chapter XIII. McGraw-Hill Book Co.

main mineral constituent of the river water and of that of fresh-water lakes, it forms the chief, indeed practically the only, important chemical deposit of fresh water.

In Bahia, Brazil, the rivers which flow in and over the older limestones are highly charged with lime in solution, and under the influence of the tropical sun, partial evaporation of the water and precipitation of the lime takes place. Thus deposits of lime ranging up to 100 feet in thickness have been formed, and they often contain plant remains as well as shells of river and land mollusks of species still living in the region. Angular as well as water-worn fragments of other rock are also included, and at times the mass becomes brecciated through local disruption and cementation of the fragments. Similar deposits are also formed around waterfalls of rivers in limestone regions in various parts of the world.

On the broad flood-plains of many tropical rivers and on their deltas are formed crusts of limestone, which are precipitated from the over-charged river water from the limestone hills. In Mexico and the southern United States these are known as *tepetate*, while the nodular limestone masses embedded with the sediments of the Indus and Ganges, in northern India, are known as *kankar*. Such limestone nodules of chemical origin are very characteristic of river sediments in arid regions, and their occurrence in older sandstones leads us to ascribe a similar origin to these deposits.

Deposits by Springs and Underground Waters

Lime Deposits of Springs. — In limestone regions, the underground water is generally strongly charged with carbonate of lime in solution. Where this water reaches the surface in springs, the relief of pressure and the escape of carbon dioxide combine to cause the precipitation of some of the carbonate of lime as a flocculent material, which later hardens to solid stone. Where leaves, mosses, or other organisms are bathed by this spring water, they are covered by a deposit of lime or are included as fossils in a mass of calcareous tufa or travertine. In ordinary spring water, the deposition of lime goes on rather slowly, but sometimes the growth of the travertine deposit is very rapid. At the Baths of San Vignone, in Tuscany, for example, travertine is deposited at the rate of six inches a year, while at San Filippo, in Sicily, the rate is one foot in four months. Here a hill, a mile and a quarter long

and a third of a mile broad, has been formed by such deposits, the height being at least 250 feet.

The water of hot springs generally carries more mineral matter in solution than that of cold springs. The cooling of the water on reaching the surface is also very conducive to lime deposition. Hence we have here extensive travertine deposits, as shown in the terraces, dams, and basins of the Mammoth Hot Springs of the Yellowstone (Fig. 182). The origin of the terraces is illustrated in the subjoined diagram (Fig. 183).

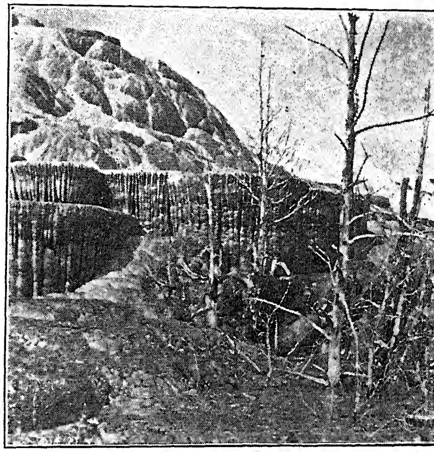


FIG. 182. — Portion of the Sinter Terraces of Mammoth Hot Springs, Yellowstone National Park.

A peculiar form of lime deposit from springs is the well-known onyx marble, or Mexican onyx, which occurs interbedded with normal tufas in Arizona, Mexico, California, and elsewhere in America, and in North Africa, Persia, and elsewhere in the Old World. This is a compact, highly crystalline, and often beautifully variegated limestone of a semi-translucent character, much used for decorative purposes, the construction of soda-water fountains, etc. It is frequently found resting on crystalline rocks in regions devoid of other limestones, and this suggests that the lime and the water which brought it to the surface were of deep-seated or magmatic origin, that is, derived from hot igneous masses within the crust of the earth.

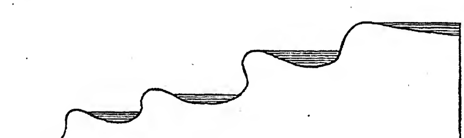


FIG. 183. — Diagrammatic section of Sinter Terraces formed by the water of hot springs. The rim of the terrace is built up most rapidly because as the water overflows it cools quickly at this point and deposits its mineral matter. Series of terrace-basins are thus formed. (From Kayser's *Lehrbuch*.)

No beds of this deposit have actually been observed in the process of making, but from the fact that it is generally enclosed by beds of normal tufa, we may assume that these deposits were formed in temporary pools or lakes where standing water prevented the rapid escape of CO_2, the rock thus becoming compact instead of porous, as is the case in ordinary tufa formed on the land.

Oölites and Pisolites Deposited by Springs. — At the famous springs of Carlsbad, in Bohemia, carbonate of lime is deposited in the form of spheroidal, discrete masses of the size of a pea, and hence forming an accumulation of particles which when bound together into a rock would constitute a pisolite. As the water rises in the springs it holds in suspension minute mineral fragments such as quartz or feldspar, which then receive a coating of lime precipitated from the water. As the particles are turned over and over in all directions like a pith-ball in a fountain jet, the coating will be uniform all over, and spheroidal masses are produced. Sometimes gas and air bubbles form the nuclei around which the lime is deposited, thus forming spheroids with a hollow center. The water of these springs is probably of deep-seated volcanic (magmatic) origin, from which source the lime is also derived. This is indicated by the fact that there are no known beds of limestone through which these waters ascend.

While no doubt both oölites and pisolites have been formed in the past by springs, the great majority of these deposits now found in the rocks of the earth's crust were formed in standing bodies of water through the influence of organic matter either directly, by the physiological activities of living organisms, such as bacteria or minute algæ, or by ammonia generated by decaying organic matter. They will be discussed in a subsequent chapter.

Lime Deposits in Caves. — The best-known types of lime deposits from ground-water are found in caverns. Two types of structures are generally recognized, the stalactite (Fig. 184), depending from the roof of the cavern or from some projecting edge, and the stalagmite, which forms on the floor of the cavern, building up a mound or pyramid, or forming a hummocky limestone floor (Fig. 185).

The formation of stalactites may be observed in tunnels and underground chambers, the roofs of which consist of blocks held together by lime-mortar, as well as in limestone caverns. Percolating ground-water will dissolve a part of this lime, and when a drop

of this lime-charged water reaches the tunnel and is suspended from the roof, rapid evaporation will cause the formation, around the drop, of a thin shell of lime. The pressure of the percolating

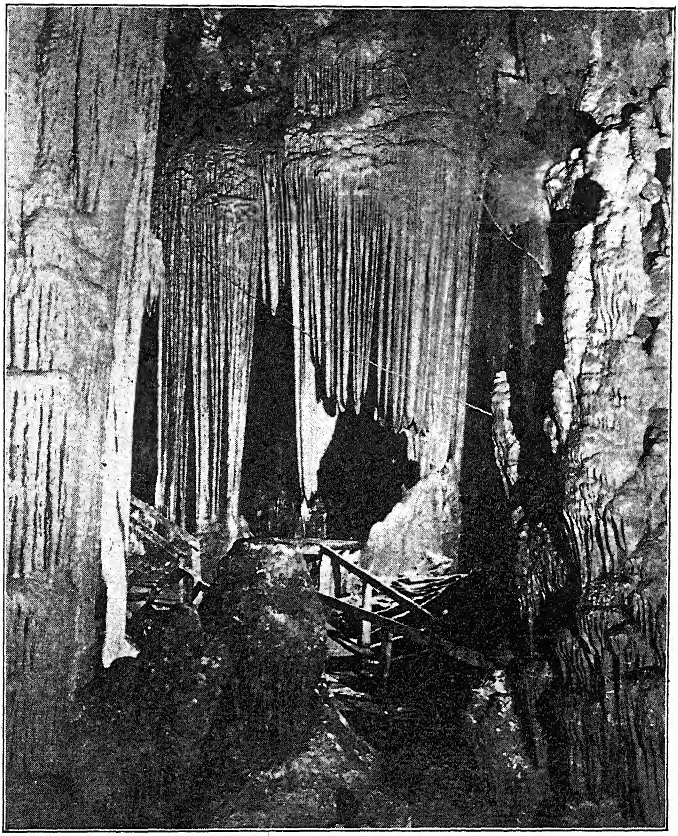


FIG. 184. — Compound stalactites and stalactic-sheets in Luray Cave, Virginia. (From U. S. G. S.)

water will cause the breaking of this film of lime, leaving only a small ring on the roof. The original drop falls, and a new one, equally charged with lime, suspends itself from the bottom of the lime ring. By constant repetition, a slender delicate tube is formed by the successive additions of minute rings of lime, and this is the basis of the stalactite. Other water, running down the outside of this tube, will thicken and strengthen it by the addition of successive layers of lime. In this process the lower end of the

initial tube is soon closed, and after that the stalactite remains a solid icicle of carbonate of lime. Neighboring stalactites may, from close juxtaposition, become confluent and form broad sheets or curtains of lime which are often beautifully banded. Such sheets of lime depending from an edge in the roof or along the line of a crack are shown in Luray Cavern, Virginia, where they form one of the striking features of this beautiful cave (Fig. 184).

Stalagmites are built up on the floor of a cavern by the evaporation of the water which drops from the roof and generally from the

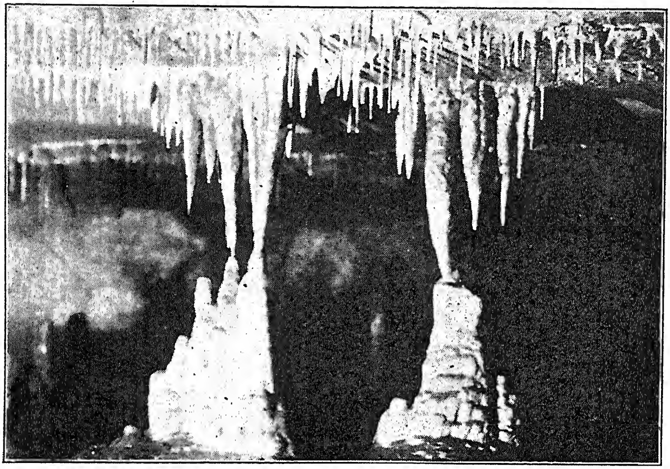


FIG. 185. — Stalactites and stalagmites in Marengo Cave, Indiana. Note the numerous small stalactites which depend from the roof of the cave, and confluence of the larger stalactites with the stalagmites to form columns.

end of the stalactite. The continued evaporation of this water leaves a minute quantity of lime, which is gradually built up into a mound, and this becomes steeper and steeper as it increases in height, and finally forms a conical or even columnar mass beneath the stalactite, with which it may eventually become joined into a continuous column. This is well shown in the above view of the interior of Marengo Cave in Indiana (Fig. 185). Many such columns may result in the cutting off of chambers and galleries from the original caverns. On the margin of the stalagmite secondary dependent stalactites are often formed, wherever a higher portion of the stalagmite projects cap-like beyond the lower. Thus highly complex and picturesque structures are produced.

Where the water spreads laterally before evaporating, an extended sheet of stalagmite material is formed, and the lateral confluence of many such sheets may result in the production of a stalagmite floor. In many of the limestone caverns of southern France and other parts of Europe, which during Palæolithic time were inhabited by the people of the Old Stone Age, implements and even the bones of these prehistoric people are found embedded in the clay of the cavern floor, over which not infrequently a cover of stalagmitic material has been formed.

Basins are also formed in caverns where water, holding the lime in solution, runs over a ledge. The edges of such a ledge cause the water to break into ripples as it overflows, and this permits the escape of some of the carbon dioxide which holds the lime in solution. In consequence, this lime is deposited at the edges of the ledge, and so a rim is gradually built up, which holds back more and more of the water in a permanent pool. Many such pools are found in limestone caves such as Luray, where the conditions for their formation are favorable. They are analogous to the sinter terraces of the hot springs (Fig. 183).

Mineral Veins

Of all the deposits formed by waters circulating in or rising through the crust of the earth, the mineral veins are the most important to man. The mineral-bearing waters which form the veins are probably in most cases hot, and they may even be in the form of vapors. These waters or vapors deposit their load of mineral matter either upon the walls of cavities or fissures, or by replacing the rock material alter it along their passageway, which may be a minute crack or other avenue of escape. The first group is called *fissure veins*, the second *replacement veins* or deposits.

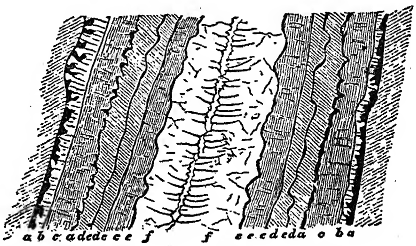


Fig. 186 *a*. — Section of the Prinzen Lode, Freiberg. *a*, blende; *b*, quartz; *c*, fluorite; *d*, barite; *e*, pyrite; *f*, calcite.

Fissure Veins (Fig. 186 *a*). — Deposition in fissures is brought about by the cooling effect produced by the walls upon the solution, or by chemical reaction with the material of the wall rock. Thus

an acid solution coming in contact with a limestone would become neutralized and lime salts inclosing other minerals and metallic substances might be deposited. Fissure veins have the form of sheets, or films, of mineral matter cutting the rock. If there is a succession of deposits, the vein will be banded parallel to the wall-rock, and the central portion may be filled with crystals. Veins of ore minerals or metallic substances contain, besides this material, quantities of other minerals such as quartz, calcite, barite, etc., and these constitute the *gangue material* of the miner. Thus native gold is commonly found in a gangue of quartz, but quartz veins without gold or other metal are much more common. So, too, are veins of calcite and other minerals of little commercial value.

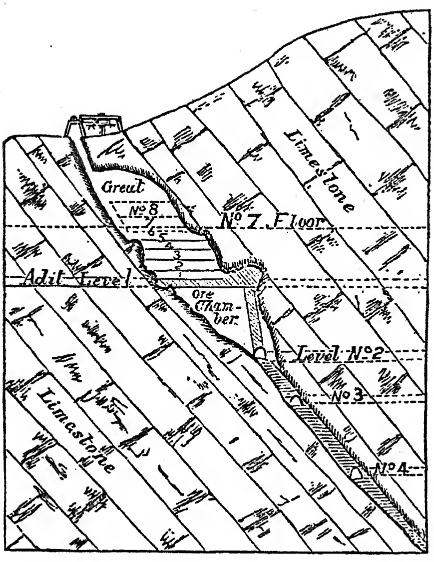


FIG. 186 *b*. — Transverse section of the great ore chamber in the Emma mine, Utah. 1 inch = 159 feet.

In rocks containing many veins there can often be recognized several distinct series of successive origin. The relative age of veins can be determined from the fact that the younger veins are continuous across the older ones which they intersect. Sometimes cavities of irregular shape in the country rock form the site of mineral and ore deposits, these differing from true fissure veins mainly in their form and extent. Deposits of this kind are called *cavity-filled ore deposits* (Fig. 186 *b*).

Replacement Deposits (Fig. 186 *c*). — Instead of filling a previously existing fissure or cavity with its deposits, the mineral-bearing waters or vapors may deposit their material as they pass through the rock, by dissolving mineral particles of the country rock and filling their places with new mineral matter. Such a replacement of one mineral by another would go on, molecule by

molecule, until an area of the rock is so replaced by, or impregnated with, valuable mineral matter as to become an important ore deposit. Frequently, of course, the replacement and fissure type of deposit may intergrade, for the walls of an open fissure may also be partly replaced by mineral matter. Veins in which ores are scattered, *i.e.* lean veins, may become locally enriched by the subsequent solution and local concentration of the valuable mineral matter. The movement of the ores is generally from higher to lower levels. Concentration may also occur by the weathering or solution and removal of the gangue material.

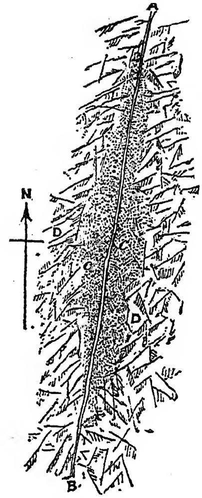


FIG. 186 *c.* — Plan of a tin lode at East Wheal Lovell Mine, Cornwall, England. *A*, *B*, leader; *C*, *C*, granite impregnated with tin ore; *D*, *D*, granite.

Placer Deposits. — Concentration of valuable minerals may also occur at points distant from the original vein. Thus quartz veins carrying gold may be broken up by the weather and the fragments washed away by the streams. On account of the greater weight of the gold, this will be concentrated in favorable areas and so form the well-known *placer deposits* (Fig. 187).

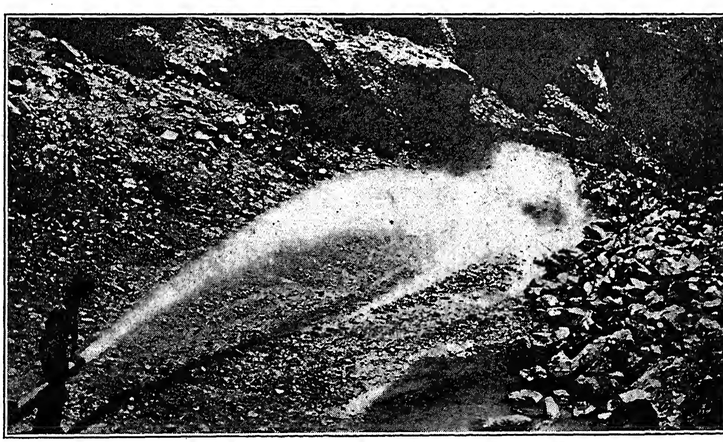


FIG. 187. — Hydraulic mining of Placer deposits (gold-bearing gravels), Colorado.

Source of the Vein Minerals. — The material in solution in the vein-forming waters or vapors may be derived either by solution from the rocks with which surface waters, descending into the earth, come in contact in their circulation through the deeper portions of the earth's crust, deriving their material chiefly from

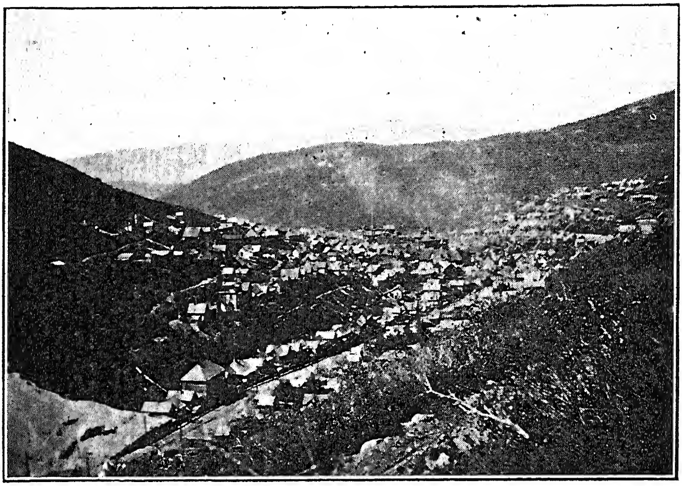


FIG. 187 *a*. — Park City, Utah, a typical mining camp. (Photo by F. J. Pack.)

rocks which overlie the point of deposition (descending solution), or the waters and vapors circulating through the rocks laterally may dissolve their ore material and deposit it on reaching the fissure (lateral secretion). Again, water derived as emanation from deep-seated igneous masses (juvenile or magmatic water) may carry upwards in solution the mineral substances derived from these masses and deposit them in the higher fissures (ascending solutions). This last mode of formation is regarded by many as the most typical origin of mineral veins.

CHAPTER XII

THE ORGANIC OR BIOGENIC ROCKS

Bioliths

By organic rocks, using that term in its strictly limited sense, we understand those additions to the lithosphere which have resulted from, or are the product of, the direct physiological activities of organisms, both animal and plant. Rocks secondarily derived from organic deposits, such as beds of limestone made of fragments worn from coral reefs, have sometimes been included under this heading, but they do not belong here, being strictly of fragmental or clastic origin. Only those deposits which are formed in place by organisms or which are largely built up of such material which has been transported and has accumulated without much wear, can be included here. Of course it must be recognized that a limestone of shells or corals, which is strictly an organic limestone, may pass laterally by degrees into one of fragmental origin. Gradation exists everywhere in nature, but we are now concerned with the study of types which may be readily recognized. The true organic rocks are conveniently termed *bioliths.*

Types of Organic Rocks or Bioliths

At the outset we must distinguish two groups of material of organic origin which enter into the formation of rocks. The first is the stony material, either carbonate of lime (with sometimes phosphate of lime) or silica, which animals and plants take chiefly from the water in which they live, and in which these minerals were dissolved. This they precipitate upon or within their tissues to build shells, corals, bones, and other hard structures. Mineral matter thus formed may be called *organic precipitates.* The second group consists of the soft tissues of organisms, such as the flesh of animals and the tissues of plants, the latter made up in large part of the substance called *cellulose.* Such *organic tissues,* as they

may be called, are much more perishable than are the organic precipitates, which are generally preserved during long periods of geological time without undergoing much alteration. Organic tissues, on the other hand, undergo decay as soon as death has ensued, and if not protected, they will quickly disappear by changing into gaseous and other matter. When protected, however, by burial, the change is commonly incomplete, and a product, largely composed of carbon and hydrogen, remains behind. The least altered of such products may form beds of coal; the more completely altered products form various bitumens. Because these substances are all more or less subject to consumption by fire, they have also been called *caustoliths* or *caustobioliths* (καυστικός = capable of burning). In the present chapter we shall consider the stony deposits of plants and animals, and in the next one the deposits formed by the organic tissues and the materials resulting from their decay.

Kinds of Rock Material Produced by Precipitation of Mineral Matter from Solution by Organisms

Here again we may distinguish two main types according to the composition of the material precipitated, namely, the *calcareous* and the *silicious* bioliths. There are others, such as certain iron oxide deposits, which are formed by the agency of organisms, but they are of minor importance. The calcareous group may again be subdivided into those in which the material is carbonate of lime (calcite, aragonite, etc.), with more or less magnesia, and those in which it is largely phosphate of lime.

Deposits of Carbonate of Lime by Plants

Deposits of carbonate of lime are formed by plants as well as by animals and are among the most abundant precipitates in the sea, though important ones are also formed in fresh water. Only two groups of plants are active in precipitating carbonate of lime, the Bacteria and the Algæ, and in each group only a limited number are active in this way.

Lime Deposited by Bacteria

Bacteria are microscopic plants of extremely simple organization, but of almost universal distribution and vast abundance. Certain bacteria (called denitrifying) which live in the warmer

portions of the sea effect the reduction of nitrates in the water to ammonia, which, with carbon dioxide, produced by other bacteria, forms ammonium carbonate. This reacts with the calcium sulphate in the sea-water, and the result is the formation of calcium carbonate. The reaction is:

$$\underset{\substack{\text{Calcium}\\\text{Sulphate}}}{CaSO_4} + \underset{\substack{\text{Ammonium}\\\text{Carbonate}}}{(NH_4)_2CO_3} = \underset{\substack{\text{Calcium}\\\text{Carbonate}}}{CaCO_3} + \underset{\substack{\text{Ammonium}\\\text{Sulphate}}}{(NH_4)_2SO_4}$$

The calcium carbonate separates out in the form of small spherical or elongated grains, which accumulate as a mass of such discrete particles and form a deposit of oölite. Such deposits are forming to-day in great abundance off the Florida coast and near the islands of that region. The most common form of the denitrifying bacteria has been named *Pseudomonas calcis*, in allusion to the fact that it precipitates lime. It is illustrated in Fig. 188, greatly enlarged.

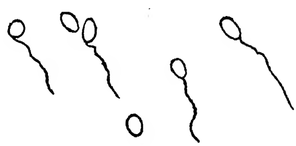


FIG. 188. — *Pseudomonas càlcis*, lime-precipitating bacteria; greatly enlarged. (After Kellermann.)

Algæ and Algous Limestones

The term *alga* (plural *algæ*) is applied to one of the lowest divisions of plants. Most algæ inhabit the sea, though many also live in fresh water. They range in size from microscopic forms to the giant kelps of the Pacific Ocean, which sometimes grow several hundred feet in length, and are important because they contain both potash and iodine. A number of algæ precipitate lime-carbonate upon and in their tissues, and so form stony structures, either as distinct masses or as incrustations of rocks, shells or other substances. To such structures the general name *nullipore* is applied, and while they occur in cooler waters as well, they are most common in tropical seas, where they constitute an important agent in the building of coral reefs. Many reefs consist, to the extent of more than half of their mass, of these organisms. Another important fact to be noted is that many, if not most, of these lime-secreting algæ also separate out a considerable amount of magnesium and precipitate it as the carbonate. Consequently, the rock resulting from such algous accumulations will be a limestome rich in magnesium carbonate and may approach a

dolomite in composition, especially when, by subsequent leaching, the proportional amount of calcium carbonate is reduced. An example of such a rock, formed in the ancient Triassic sea, is seen in the peaks called the Dolomites, from the character of the rock, and which are situated in the Alps of the Tyrol (Fig. 4, p. 9). The rock is known to have been largely built up from lime-secreting algæ of the genus *Diplopora* (Fig. 5, p. 10).

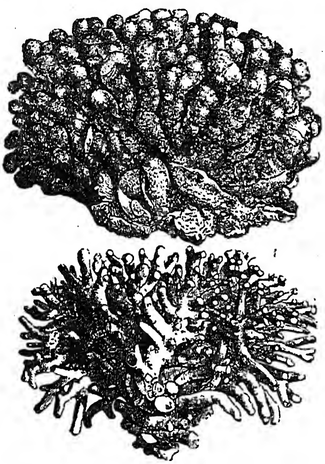


Fig. 189. — Two modern species of *Lithothamnium*, a lime-secreting alga, which plays an important part in the building of modern coral-reefs. Isle Maurice. (After Zittel.)

Among the more important types of nullipores, we may mention only a few in addition to the *Diplopora*.

Lithothamnium (Fig. 189). — This forms irregular masses with knobby and sometimes leaf-like surface features. It abounds on modern coral reefs and also formed extensive limestone masses in former periods.

Halimeda (Fig. 190). — This is a form of much more plant-like appearance, having structures resembling a stem and leaves, covered with lime, and brittle when dry. It grows in the protected lagoons of coral reefs and other regions.

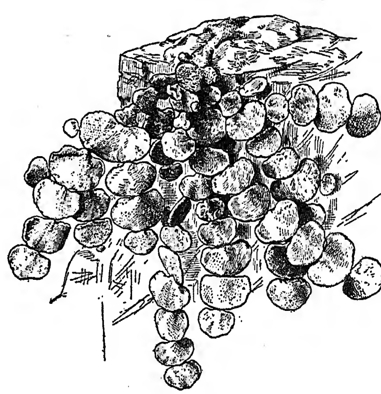


Fig. 190. — *Halimeda tuna*, a lime-secreting green alga from the modern sea; attached to rock.

Corallina (Fig. 191). — This is a pink, jointed plant, remotely resembling a finely branched coral or hydroid and common below low tide on all our North Atlantic coasts (Corallina zone). When the plant is dead and dry, the color becomes white.

Chara (Fig. 192 *a*). — Besides these and many other marine nullipores, there are

some which live in fresh and mineral-spring waters. The common fresh-water form is the *stonewort* or Chara, found in fresh-water lakes of limestone regions. It is a green alga, but appears gray from the amount of lime precipitated upon its surface. When dry, it is white and very brittle. When abundant, it forms deposits of marl on the lake-bottom. Some older limestones, such as some of those of Tertiary age which underlie the city of Paris and crop out some distance from it, are made of the crushed and more or less compacted limy filaments of this alga. Their origin

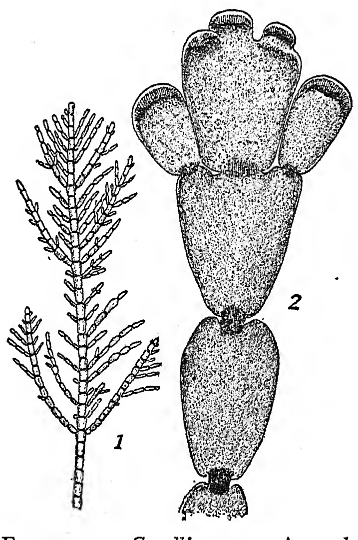


FIG. 191. — *Corallina*, sp. A modern lime-secreting alga. 1, entire plant, natural size; 2, a small branch enlarged.

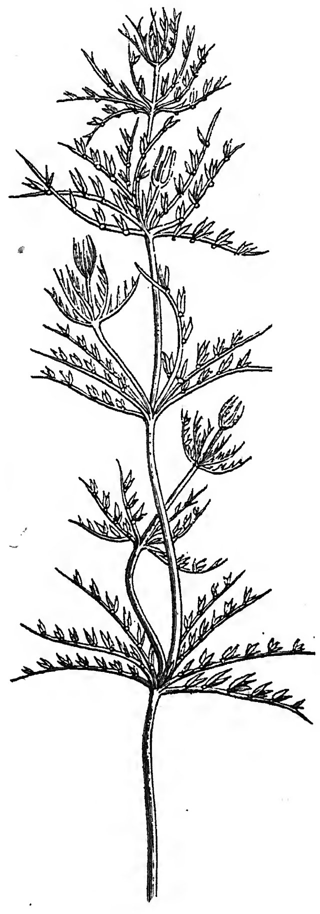


FIG. 192 *a*. — *Chara vulgaris*, Linn. A modern lime-secreting alga, growing in fresh water. An important marl and limestone former. (From Haas, *Leitfossilien.*)

from this plant is recognized by the abundance in them of the little ridged globular vessels, about the size of a pin-head, which were the spore-bearing cases of the plant. These are readily recognized by the peculiar spiral bands which surround them (Fig. 192 *b*). Such

limestones also commonly inclose the shells of fresh-water snails and other mollusca.

Filamentous algæ are also active in hot springs, separating out the lime carbonate, which then builds up the mounds and basins often found around these, as in the Yellowstone region. It is diffi-

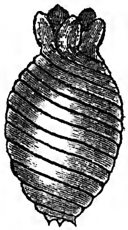


FIG. 192 *b*. — *Chara vulgaris, L.* A recent calcareous alga (fresh water); spore-vessel with corona. Enlarged. This is frequently found in great numbers in fresh-water limestones, showing their mode of origin. (From Haas, *Leitfossilien*.)

FIG. 193. — A coccolithophora. A mass of coccoliths; a marine pelagic plant of low order covered with calcareous plates. (Greatly enlarged. After Murray.)

cult to determine in any case what part of the lime of such hot-spring basins is built up by purely hydrogenic means (see *ante*, p. 261), and to what extent algæ are responsible. The oölites of Great Salt Lake and of other highly saline waters have also been regarded by some authorities as largely due to the growth and lime-secreting habit of microscopic algæ (Rothpletz).

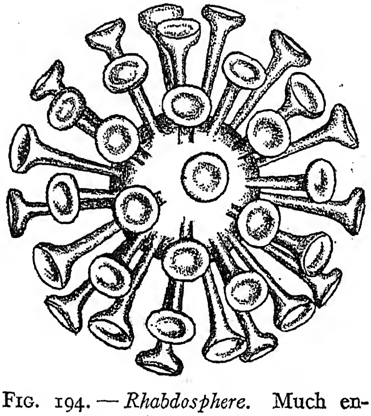


FIG. 194. — *Rhabdosphere*. Much enlarged. (After J. Murray.)

Coccoliths, etc. — Finally, we may mention certain floating organisms in the sea, generally regarded as extremely low types of plants called *Coccolithophores* (Fig. 193), which are covered with an armor of plates. These plates, according to their form, are called *coccoliths*, *discoliths*, *cyatholiths*, etc. When covered with rods they are called *rhabdoliths*, and form a *rhabdosphere* (Fig. 194). These structures are found in calcareous oozes which

remain on the floor of the deeper parts of the oceans and which are largely composed of minute shells of Foraminifera (Globigerina ooze), to be described next.

Foraminifera and Foraminiferal Oozes and Limestones

The name *Foraminifera* is given to one of the classes of the lowest group of animals, the *Protozoa*, in which each animal secretes a small shell of carbonate of lime, to which successive chambers are added as the animal grows, all the chambers being occupied by the living animal tissue. Many of the shells are pierced by holes, as in the modern *Globigerina* (Fig. 195), through which delicate threads of living matter (*pseudopodia*) project, which serve to collect food. There are many varieties of these shell-bearing Foraminifera in the modern ocean (Fig. 196).

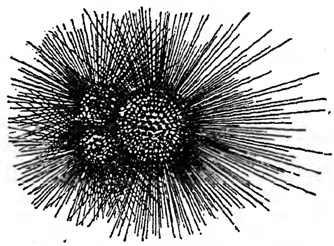


Fig. 195. — *Globigerina bulloides.* A modern pelagic foraminiferan, with expanded pseudopodia. (After Wyville Thompson.)

Globigerina Ooze. — Globigerina is the most common among the floating organisms in the upper layers of the sea-water. Its shell consists of a number of chambers of increasing size, the whole forming a globular mass (Fig. 196, 2). Upon the death of the animal these shells slowly sink to the bottom (this requiring from three to six days), and if they are not dissolved again in the process, as happens in

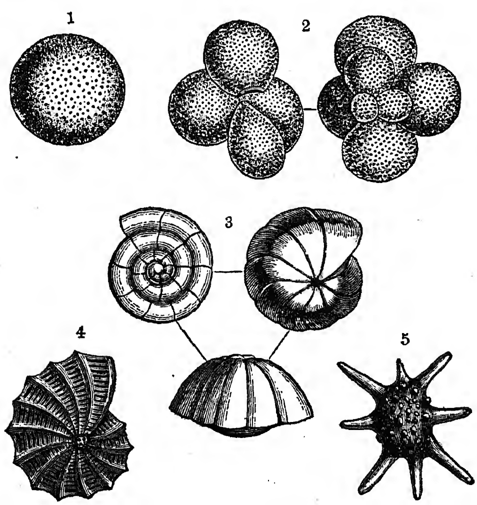


Fig. 196. — Modern Foraminiferal types. Much enlarged. 1, *Orbulina;* 2, *Globigerina;* 3, *Rotalia;* 4, *Polystomella;* 5, *Calcarina.* (After Neumayer, *Erdgeschichte;* from Ratzel, *Die Erde.*)

very deep water, they will accumulate upon the floor of the ocean as a *Globigerina ooze* (Fig. 197), made up largely of this shell, but of others as well and of coccoliths and other organisms, including non-calcareous types. This ooze is most abundant in depths between 2500 and 4500 meters, the percentage of lime carbonate decreasing from 70 per cent in the lesser to 50 per cent in the greater depths, where more of the shells have been dissolved. Nearly 30 per cent of the area of the sea-floor is covered with this Globigerina ooze, its greatest distribution being in the Atlantic and its least in the Pacific, with the Indian Ocean intermediate (Fig. 198).

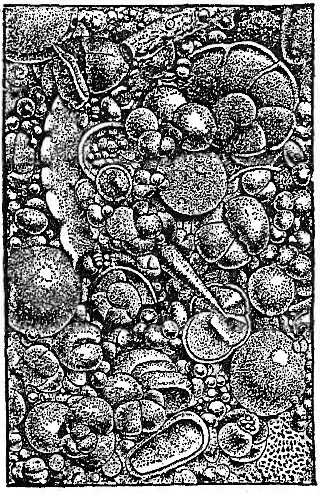


FIG. 197. — Globigerina ooze, from the deep sea, enlarged about thirteen times. (After Murray and Renard.) Besides the foraminiferan shells there are pteropods, ostracods, and other organic structures.

An Older Globigerina Limestone. — An example of a limestone now exposed above sea-level, but formed as a Globigerina ooze in deep water, is found on the Island of Malta in the Mediterranean. The age of this rock is older Tertiary (Oligocene), but nearly 40 per cent of the species whose shells compose this rock still live in the neighboring waters of the Mediterranean. Most of the minute shells of which the rock is composed are those of Globigerina. Scattered among them are nodules of phosphate of lime similar to those found in the deeper ocean waters of to-day. Altogether, this limestone, now a solid rock, represents admirably a former deep-sea deposit of Globigerina ooze, which, in the course of time, has solidified and been lifted above sea-level by earth-movements of the kind to be discussed in a subsequent chapter. Such old Globigerina limestones occur in other districts as well.

Shallow Water and Terrestrial Foraminiferal Deposits

On tropical coasts, especially those of coral islands, shells of dead Foraminifera often accumulate in large quantities, but these are only exceptionally the shells of Globigerina, other forms which live

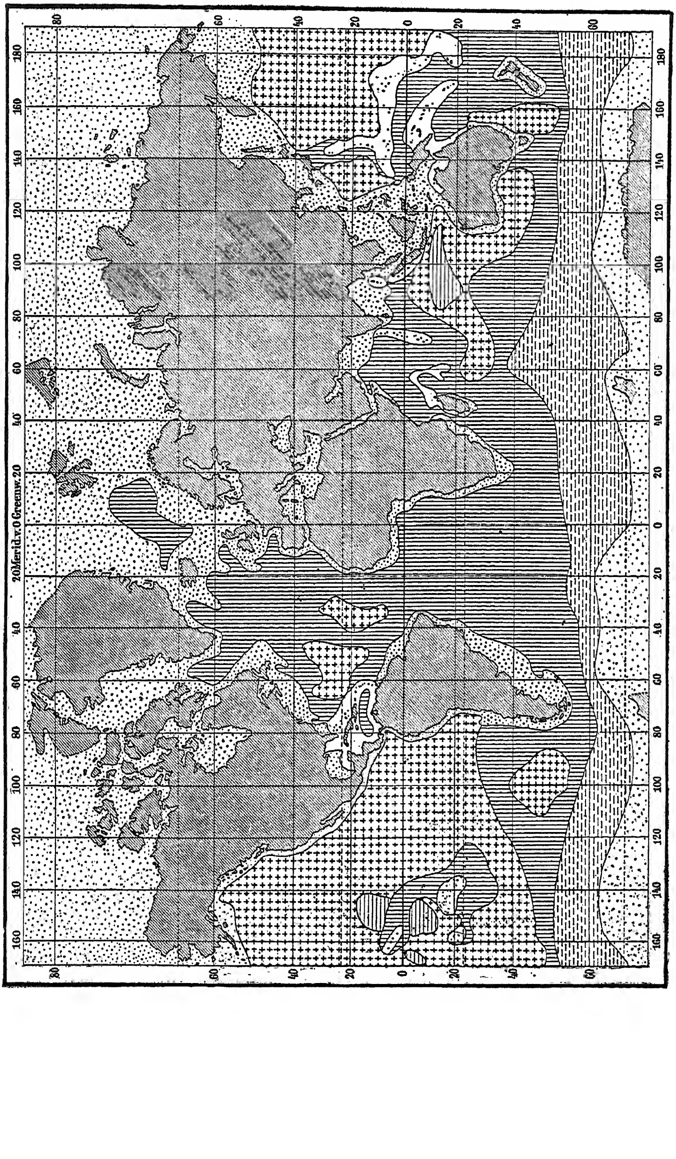


Fig 198. — Distribution of sediments in the modern sea, after Murray and Renard. *Dotted*, terrigenous deposits; *white*, coral sand and mud; *horizontal lines*, radiolarian ooze; *horizontal broken lines*, diatomaceous ooze; *vertical lines*, Globigerina ooze; *crosses*, deep sea clay. (From Kayser's *Lehrbuch*.)

in shallow water predominating. Owing to the lightness of these shells, they are often carried far inland by the wind, forming dunes

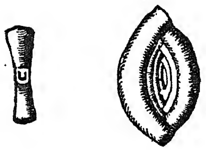


Fig. 199 *a*. — Foraminiferal shell, Miliola type. (*Spiroloculina badensis* d'Orbigny. Miocene, Baden.) Lateral and top views. Important limestone builder. (From Haas, *Leitfossilien.*)

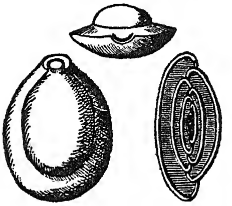


Fig. 199 *b*. — A foraminiferal shell of the Miliola type. (*Biloculina inornata* d'Orb. Miocene, Baden.) Note that each new chamber covers all preceding ones. Two views and section. Important limestone builder.

and even extended deposits chiefly composed of them. In the western part of India (Kathiawar Peninsula) such a limestone, called the Junagarh limestone, from the city of that name which is built upon it, overlies the Deccan trap at a distance of thirty miles from the sea. It has a thickness probably exceeding 200 feet, and its cross-bedded structure indicates wind transportation (see Chapter XVI). It is almost entirely made up of foraminiferal shells and other lime particles, with only from 6.5 to 12.5 per cent of silicious material. The chief foraminiferan shell of this rock is known as *Miliola* (Figs. 199 *a*, *b*), on which account the rock is called Miliotic limestone. Such limestones are found on the Arabian peninsula and elsewhere, and in Tertiary deposits as well.

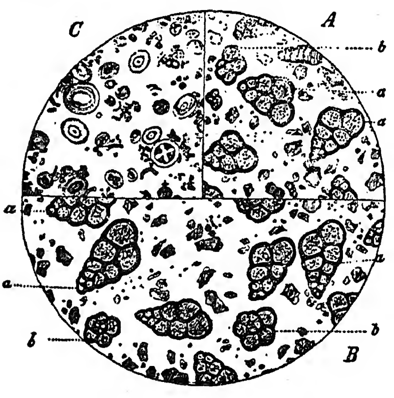


Fig. 200. — Thin sections of chalk as seen under the microscope. *A*, chalk from Sussex, England, enlarged 60 times; *B*, chalk from Farafrah, Libyan desert, enlarged 60 times; *C*, dried residue of milky chalk-water with coccoliths, enlarged 700 times; *a*, *Textularia globulosa*; *b*, *Rotalia* (*Discorbina*) *marginata*. (After Zittel.)

Chalk. — This is a white, soft, friable rock, which consists of minute shells and fragments of shells of Foraminifera, of coccoliths

and of other calcareous structures, all of them exceedingly minute. A properly prepared slide (Fig. 200) of the material, from which the finest dust has been washed out, shows, under the microscope, a number of scattered shells of Foraminifera, of which a form of triangular outline and composed of a double row of constantly increasing chambers is the most abundant. This form, known as *Textularia globulosa* (Fig. 200 *a*), lives to-day in the estuary of the Dee River near Chester, England, and, like the other common species

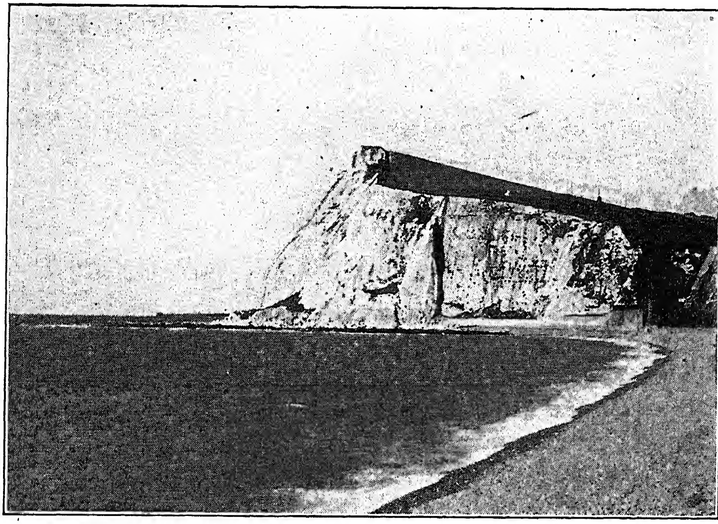


FIG 201. — Wave-cut cliff in chalk beds near Dover, England. From D. W. Johnson's *Shore Processes*. By permission of John Wiley & Sons. The chalk is in large part composed of microscopic shells and other calcareous organic structures as shown in section under the microscope (Fig. 200). See also the view of the Chalk Cliffs on the French coast, Fig. 713.

of the chalk (*Rotalia marginata*, Fig. 200 *b*), is therefore a shallow-water species and not a surface floater (*plankton*) as is Globigerina. From this and other facts it appears that the chalk is not a deep-water deposit, as is the Globigerina ooze, but was formed in shallow water, and the absence in it of quartz sands and of clays must be accounted for by assuming that the lands which could supply such material were too low to affect the deposits.

The chalk forms extensive beds over northern France and Belgium and the south and east of England. These beds were once continuous across the Channel and over much of the North Sea,

while at the same time they extended as far to the northwest as northern Ireland. The cliffs which they now present to the sea and inland are the result of subsequent erosion (Fig. 201; see also Chalk Cliffs of Fécamp on the French coast, Fig. 713). The flints in the chalk (Fig. 162, p. 224) are the result of secondary segregation of silica which originally was scattered through it, and which originated from the silicious skeletons or other parts of marine organisms (Radiolaria, sponge spicules, etc.). At certain levels in the chalk, beds of marine shells or other organisms are found, indicating a temporary cessation of the chalk-forming conditions and the inauguration for a time of normal beach or shallow sea deposition. The possibility that some chalk beds may be formed by the drifting inland of shells and fragments of lime by wind, analogous to the Miliolitic limestone of India, has been suggested.

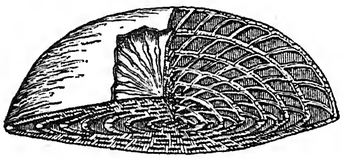


FIG. 202. — Shell of a Nummulite cut transversely and in part horizontally. Enlarged. (Group of *Nummulites lucasana* Defr. Eocene, Bavaria. From Haas, *Leitfossilien*.)

Nummulitic Limestone. — Over large areas of southern Europe and northern Africa, and in parts of Asia as well, occur thick deposits of limestones which are largely or almost wholly composed of disk-like or button-like bodies, varying in size from that of a pinhead to an inch or more in diameter. From their resemblance to coins, these bodies have long been known as *Nummulites*. When worn, broken, or cut, they show a characteristic internal structure, with regular division into chambers (Fig. 202), and they are recognized as belonging to the class of Foraminifera, of which they constitute a remarkable, gigantic, but now wholly extinct type. These rocks all belong to the early Tertiary period, and in Egypt they have been quarried since the days of Herodotus and before, and they were extensively used in the facing of the Great Pyramid (Fig. 28, p. 76). A section of such limestone from the

FIG. 203. — A fragment of Nummulitic limestone from the Pyrenees. The nummulites are shown in section, and of natural size. (After Haas, *Leitfossilien*.)

Pyrenees is shown in Fig. 203. These large Foraminifera probably lived in shallow water, as do their nearest modern relatives.

FIG. 204. — *Orbitoides* (*Lepidocyclina*) *kempi*, O'Connell. Enlargement of a single shell in section. Cuba. (After M. O'Connell.)

Some of the limestones of our Gulf Coast States (Vicksburg limestone), and those of the West Indies and elsewhere, are largely composed of related Foraminifera. One of these, on the island of Cuba, is made up entirely of the shells of such a form (*Orbitoides*), somewhat larger than a pinhead; an enlarged photographic view of one of these is reproduced in Fig. 204. Similar limestones of great thickness occur in Jamaica. It is not impossible that these were formed after the manner of the Miliolitic limestone of India (Junagarh Limestone) described above, the shells being blown inland from the coast. This is suggested by the almost total absence of other organisms.

Fusulina Limestone. — Another type of limestone, also formed of large foraminiferal shells, is found in the upper Palæozoic series (Pennsylvanian and Permian) of western North America, Europe,

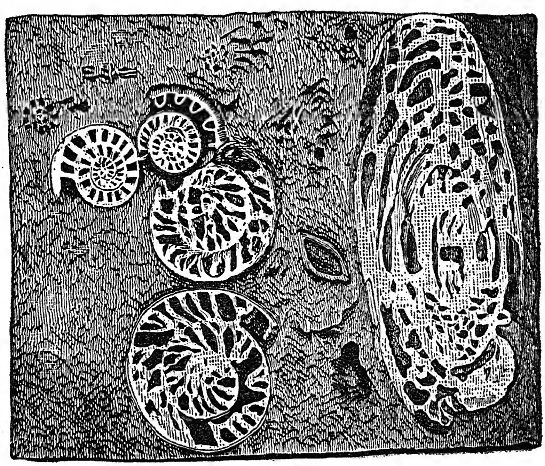


FIG. 205. — A polished piece of *Fusulina* limestone of the Carbonic. Enlarged nine times. On left sections cut the Fusulina transversely, on the right obliquely to the longitudinal axis. (From Haas, *Leitfossilien*.)

and Asia. An enlarged section of such a limestone is shown in Fig. 205. These foraminiferal shells frequently resemble a kernel of rice; they are elongate and spindle-shaped (*Fusulina*, Fig. 206)

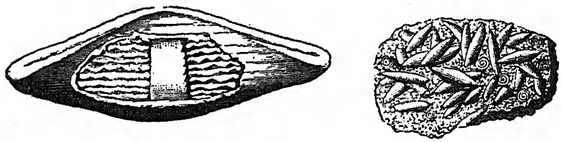


FIG. 206. — *Fusulina cylindrica*, a typical foraminiferal shell forming rocks in the later Palæozoic. A group natural size, and a single shell much enlarged and partly sectioned to show interior. (After Kayser.)

or more or less like a football in form (*Schwagerina*, Fig. 207), but seldom more than a fraction of an inch in greatest diameter. They are restricted to that part of the geological series, becoming extinct with the close of the Palæozoic era, though a form of similar appear-

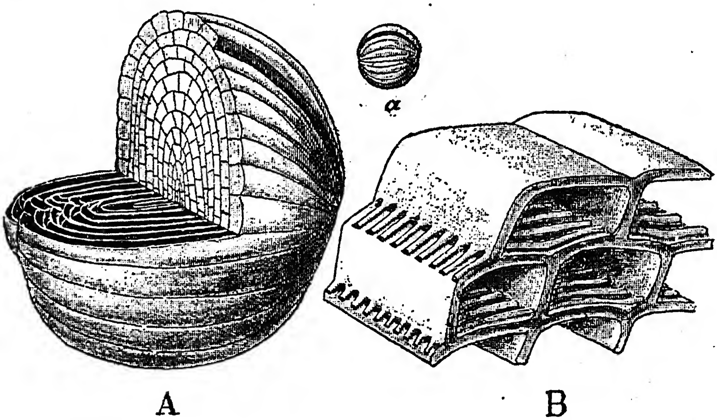


FIG. 207. —*Schwagerina verbecki*, Geinitz. A, diagrammatic view; B, plan of structure; *a*, natural size. (After Schwager.)

ance, but very different structure, occurs in Tertiary rocks. In general, the Fusulina is like a Nummulite with the axis of coiling greatly elongated. Since the Fusulinæ indicate the horizon of the oldest extensive coal deposit, their recognition is of importance. This will be more fully discussed in a later chapter.

CORALS AND RELATED REEF-BUILDING ANIMALS

Corals and Coral Polyps. — The name coral is applied to the hard structures (usually of carbonate of lime), built by delicate and

as a rule small animals, which live only in normal sea-water and mostly in regions of tropical or subtropical climates. The animals are called *polyps*, and they are more or less cylindrical, fleshy, but very delicate organisms, closed at the bottom, but having a central opening, the mouth, at the top, around which there are one or more rings of tentacles. In the simpler forms, which are known as *hydroid polyps*, the entire interior of the body-cylinder is hollow and constitutes the stomach; but in the *coral polyps* proper (Fig. 208), the interior is variously modified, chief among the modifications being a series of fleshy plates which extend from the bottom to the top of the cylinder and divide the inner cavity into a number of radial chambers.

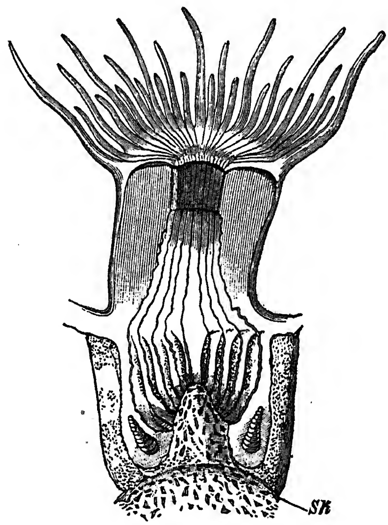


FIG. 208. — Vertical section through a polyp greatly enlarged (*Astroides calycularis*). (After Lacaze-Duthiers.) Mouth surrounded by tentacles and beneath it the "stomatodæum." The fleshy mesenteries are shown, and the calcareous septa which lie between them in position. In the center of the bottom is the columella arising from the calcareous basal plate (Sk). (From Hass, *Leitfossilien.*)

Not all polyps secrete a hard structure, but those that do so precipitate the lime from the sea-water in and upon the outer layers of their body, especially at the base of the cylinder. These hard structures begin as needles or *spicules* of lime, which in some groups, the *gorgonias*, seldom or never unite into a solid mass, but remain scattered in the fleshy parts of the body and are left as lime needles upon the decay of the flesh. In other groups, however, these needles are so numerous and crowded that they become welded into a solid, more or less porous, stony mass, the true coral. Of this, two types may be recognized, the *solid rod* and the *star coral*. The first of these is built by a colony of polyps which are bound together by a solid fleshy substance into a cylinder of living matter, over the surface of which the individual polyps are scattered. The hollow central axis of the mass is

filled by the carbonate of lime which this fleshy mass separates from the sea-water, and when this central calcareous rod is stripped of the surrounding fleshy substance, it appears as a much branching solid structure of carbonate of lime, colored a deep pink or red in the most familiar types. This is the precious coral of commerce, from which coral beads and ornaments are cut. In the more common, but less familiar gorgonias, the sea-fans and sea-whips, so abundant on most coral reefs, this central axis is horny instead of calcareous, but is otherwise much of the same character. The lime secreted by the gorgonias, as already stated, is de-

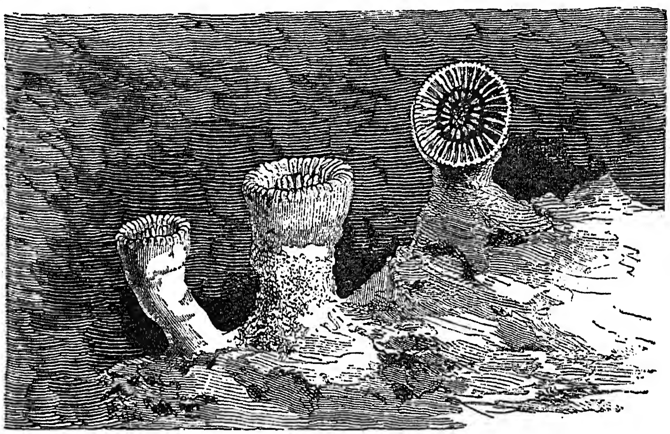


FIG. 209. — A simple cup-coral (*Caryophyllia cyathus*), attached to the sea-bottom. (After Dana, *Corals and Coral Islands*, by permission of Dodd, Mead & Co.)

posited as lime needles or spicules in the fleshy mass which surrounds and builds the horny axis. These spicules are sometimes of importance in the formation of modern limestones.

Far more abundant than the group just described, and of more importance in the formation of organic limestones, are the *star corals*. These are so called because they show upon their surfaces one or many, generally more or less depressed, circular, oval, or polygonal areas or cups, each of which contains a radial series of vertical plates, which converge toward the center of the cup and give the appearance of rays from a central star. These rays are called the *septa*, and they correspond to the radial fleshy plates within the body of the coral polyps by the base of which they are deposited.

We may recognize *simple corals* with only one septa-bearing cup, which then is either circular or oval (Fig. 209), and *compound corals*, in which many such cups occur side by side, separated by intervening limestone material, when their outline is circular or oval,

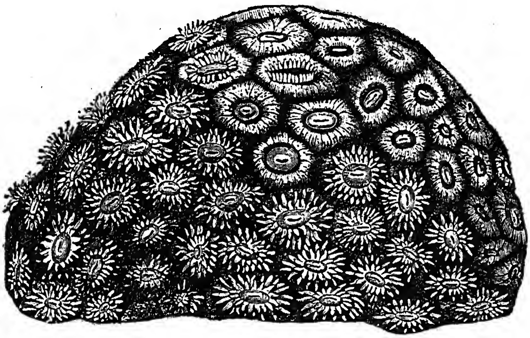


FIG. 210. — Compound coral head (*Astræa pallida*), with polyps partly expanded and partly contracted. The expanded polyps show the tentacles which surround the mouth; the contracted polyps show the polygonal outline from crowding. (After Dana, *Corals and Coral Islands*, by permission of Dodd, Mead & Co.)

(Fig. 210) or closely crowded, when they assume more or less polygonal forms (Fig. 211). But always the septa radiate from the center of each cup to its margins. Sometimes the cups are so minute and separated by such broad intervals of spongy lime matter, that the mass has a more or less homogeneous appearance, the cups

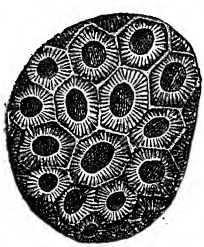


FIG. 211. — A compound coral head with crowded prismatic corallites (*Acervularia ananas*). The specimen represents a worn pebble, formerly a part of a larger head. (From Kayser.)

being recognized only on careful examination, as they are small. Often they form closely crowded tubes (*Madrepora*, Fig. 212); at other times a massive branch is covered with a closely-set series of minute cups (*Porites*, Fig. 213). In still other coral heads the cups

or calices are confluent, producing sinuous valleys and ridges (Fig. 214).

Some of the ancient corals which were important as limestone makers consist of a series of tubes arranged either in a loose, more

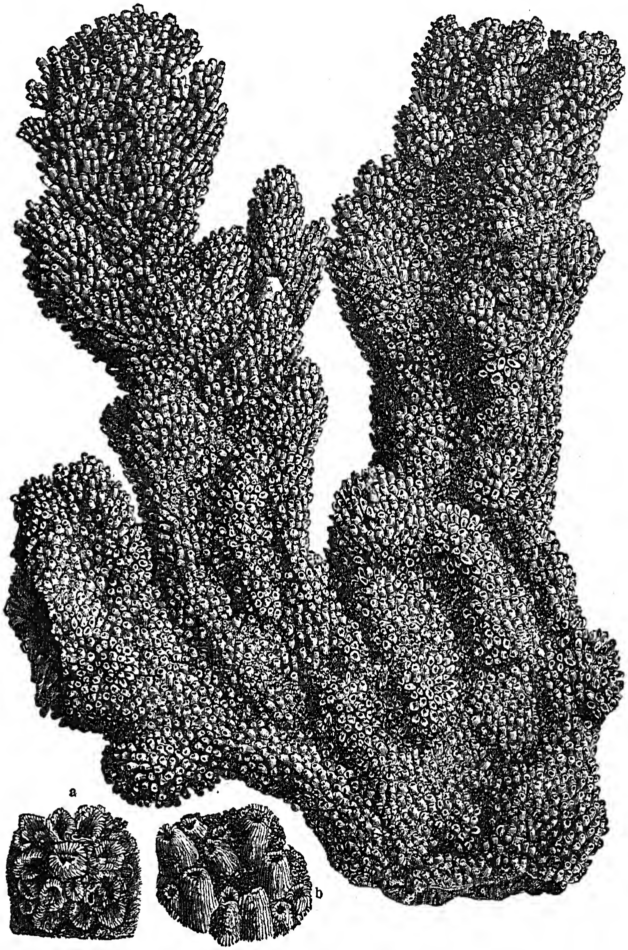


FIG. 212. — Reef-coral, *Madrepora palmata*, natural size, and *a* and *b* slightly enlarged calices. (After A. Agassiz; from Ratzel, *Die Erde*.)

or less chain-like series (chain coral or *Halysites*, Fig. 215) or closely crowded and taking on a columnar prismatic form from crowding (honeycomb-coral or *Favosites*, Fig. 216, and *Columnaria*). In these corals the septa are generally very short, or they may be

represented by vertical rows of spines, or again they may be absent altogether. Instead, the tubes are divided by numerous horizon-

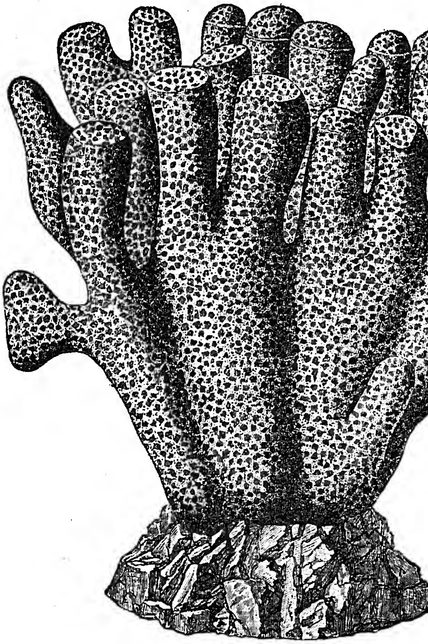


FIG. 213.—A massive branching coral (*Porites mordax*) with very small calices; an important reef-builder. (After A. Agassiz; from Ratzel, *Die Erde.*)

tal partitions which are often so closely crowded as to give the tube, when broken lengthwise, a finely cellular structure (Fig. 216).

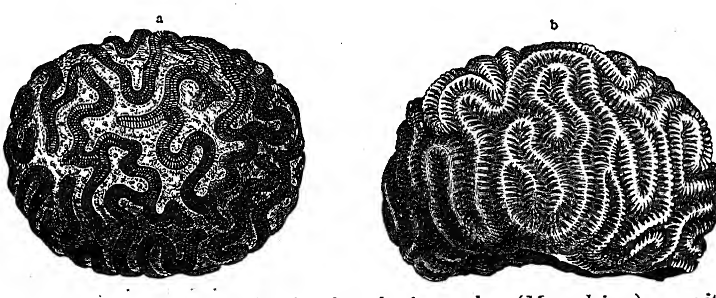


FIG. 214.—Two small heads of a brain-coral. (*Mæandrina.*) *a*, with soft parts; *b*, corallum. Slightly reduced. (After Brehm; from Ratzel, *Die Erde.*)

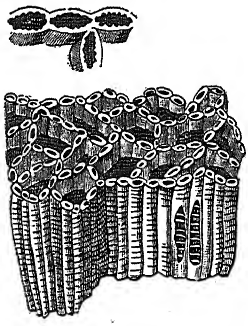


FIG. 215.—The chain coral. (*Halysites catenularia*, E. and H.) Silurian; with enlargement of a few corallites. This is an important index fossil of the Silurian, and an important limestone builder as well. (From Haas, *Die Leitfossilien.*)

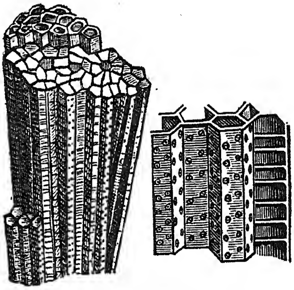


FIG. 216.—A characteristic a-septate compound coral. (*Favosites gotlandica.*) Silurian. The columns are prismatic and their walls pierced by regular pores. Internally the tubes are divided by horizontal plates or tabulæ. This is an important limestone builder in the Palæozoic. (From Haas, *Leitfossilien.*)

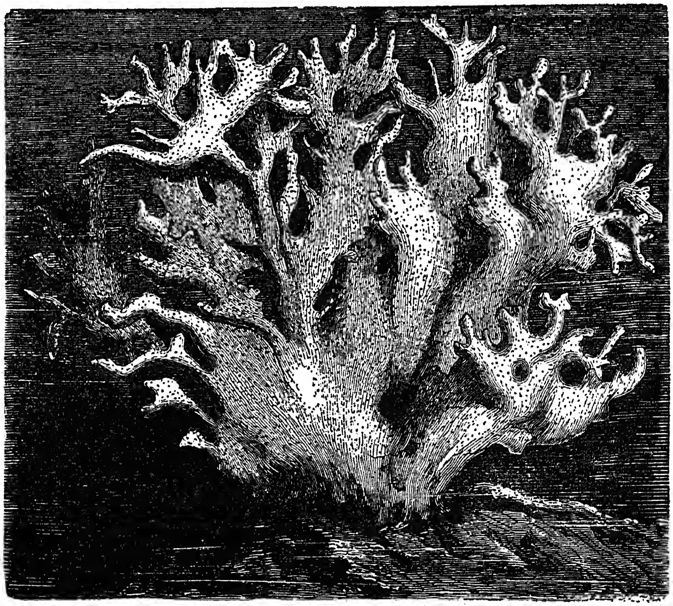
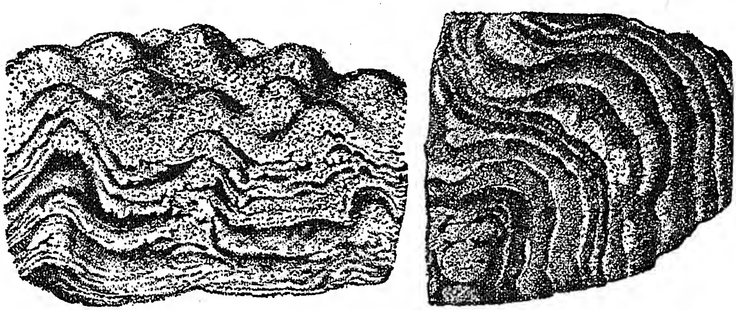


FIG. 217.—A modern hydrocoralline (*Millepora alcicornis*). Important as a reef-builder. (From Dana, *Corals and Coral Islands*, by permission of Dodd, Mead & Co.)

Hydroid Polyps and Hydrocorallines. — Finally the hydroid polyps which, it will be remembered, have no internal fleshy radiating plates, sometimes build calcareous coral-like structures in which, however, the cups are merely holes in the more or less solid-appearing limestone mass (*Millepora*, Fig. 217) which forms the structure secreted by them and to which the name *hydrocoralline* is applied.

Such hydrocorallines often form important and extensive portions of coral reefs, the form known as *Millepora* (referring



A *B*

FIG. 218. — Fragments of large masses of stromatoporoids, which were important reef-builders in the Palæozoic. *A*, *Stromatoporella tuberculata*, a weathered fragment showing the hummocky surface, and the successive layers (Devonian); *B*, *Stromatopora antiqua*, a transverse polished section of a fragment showing the coarse concentric layers (Silurian). (After Nicholson; from Grabau and Shimer, *North American Index Fossils*.)

to the thousands of pores on the surface, *i.e.* the cups) abounding on certain modern coral reefs, while another, the *Stromatopora*, sometimes makes up the main portion of ancient (Palæozoic) coral reefs, growing in masses up to ten feet in diameter. It is readily recognized by the concentric arrangement of the successive layers of which this mass is composed (Fig. 218). Each layer will, on microscopic examination, show a very definite structure such as is found only in limestone deposits of organic origin. Without careful examination of details, however, the student will not be able to distinguish the numerous kinds of Stromatoporas from one another, nor will he be able readily to distinguish them from ancient limestone masses of similar concentric structure built by marine or even by fresh-water plants of low order (Algæ, *e.g.* *Cryptozoön*, etc.).

Characters and Types of Modern Coral Reefs

Corals commonly grow associated in regions of the sea where minute food particles are abundant, where the mean temperature of the coldest months does not usually fall below 21 degrees C., or the minimum annual temperature below 18° C. and where a favorable hard bottom, free from silt, exists for their attachment. For it must be noted that the coral polyps are not free-moving or floating organisms (except in their larval stages), but attach themselves to the sea-bottom and lead a sedentary existence. By such association in growth of corals, together with other lime-secreting organisms, a reef is built up which rises toward the level of the sea, and may grow so high that it is exposed at very low tides for a short period of time. Coral reefs must be distinguished from coral islands (see Fig. 220), which represent a stage subsequent to the reef when, by wave action, the broken-off dead coral-masses and coral-sands are heaped up to such an extent that they permanently project above the water. Reefs, on the other hand, are always submerged except for the short period of lowest tides already referred to. Modern coral reefs are chiefly confined to the region limited by the 28th degree north and south latitudes, the Bermuda Islands, bathed by the warm Gulf stream, being the chief exception to this, lying in latitude 32° N. This distribution is partly due to the inability of polyps to separate out much lime from sea-water in colder regions, and also because whenever ice forms in winter the coral polyps, always growing near the surface of the sea, are readily destroyed by such ice. On this account we may confidently assume that ancient coral reefs required similar warm temperatures for their formation, and if we find that rocks now exposed in the Arctic regions are formed from ancient coral reefs, as are those on the North Siberian islands, we must assume that at the time of their formation this region had a more tropical climate.

In the second place, reef-building corals flourish best in shallow water, usually in water not over 20 to 25 fathoms (120 to 150 feet) in depth,[1] though some occur at greater depths. Many of them flourish so near the surface of the sea that they are exposed at low tide, as is so finely shown in the wonderful series of photographs obtained by Saville-Kent from the Great Barrier Reef of Australia

[1] Vaughan considers 45 meters the maximum.

(Fig. 219).[1] Frequent agitation of the sea-water is necessary to the active growth of coral polyps, and as a rule, strong light is required. The salinity of the water must not, as a rule, fall much below 27 per mille, nor rise much above 38 per mille, though coral polyps have been found to flourish in very brackish and very saline waters.

Reefs vary greatly in the types of organisms which built them. In nearly all of them calcareous seaweeds, or nullipores, play an important part, and some reefs are largely composed of them. In

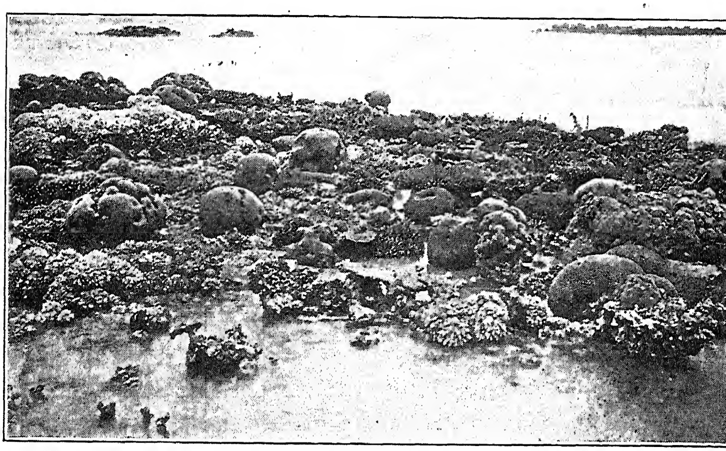


Fig. 219. — Portion of the Great Barrier Reef of Australia at very low tide, showing the living coral masses growing close together, and withstanding the periodic exposure. (After Saville-Kent.)

others, hydrocorallines (*Millepora*, Fig. 217) abound, while in still others the gorgonias form an important, if not dominant element. Star-corals are always present, and in many cases predominate, comprising both the branching types such as the staghorn coral (*Madrepora*, Fig. 212), the fringe coral (*Porites*, Fig. 213), etc., and the massive or head types, such as the star corals proper (*Astræa*, etc., Fig. 210), the brain coral (*Mæandrina*, Fig. 214), and many others. Besides these reef-builders proper, there are many other animals which live in and about the coral branches, and many of them have hard shells or other structures which, on the death of their possessors, add calcareous material to the growing mass.

[1] The student should examine the photographs published in Saville-Kent's book on the *Great Barrier Reef*.

According to their location, we may distinguish two groups of reefs: 1, the *oceanic*, and 2, the *epicontinental*. The first have no direct relationship to the continents, but grow around islands in the open oceans or form separate rings of coral islands or *atolls*. The second group is marginal to the land, being built upon the continental platform or in seas which indent the continents. Between the two there is a gradational series, but on the whole they are quite distinct.

Oceanic Coral Reefs

Of these, three types are recognized; namely, fringing reefs, barrier reefs, and atolls.

The Fringing Reef. — This grows close around volcanic or other islands, from the submerged slopes of which it rises, and is separated from the island it fringes by a very narrow channel.

The Barrier Reef. — This grows at a distance of several miles from the shores of the oceanic island, thus leaving a broad strip or channel of water between it and the island. This water may be from one or two to as much as 30 or 40 meters in depth. The barrier reef of New Caledonia in the Pacific is 400 miles long and about ten miles distant from the shore. The outer or seaward margin of such a barrier slopes off into much deeper water than is the case with that of the fringing reef, and the inner channel, besides being broader, is also much deeper than that of the fringing reef. This channel is connected with the outer ocean by cross channels cut through the reef, and these are kept open by the ebb and flow of the tide.

The Atoll (Fig. 220). — This consists merely of a ring of coral-reef islands in the open ocean, with no land in the center of the ring, but instead a shallow lagoon of quiet water. This lagoon is connected with the open sea by cross channels, which are located on the leeward side of the atoll, and so generally form a protected entrance to a quiet inner harbor. The water around the atoll is generally very deep, and the outer slopes of the reefs are steep. At the Kokos Keeling atoll, in the eastern part of the Indian Ocean, for example, the ocean has a depth of 1200 fathoms at a distance of only 2200 yards from the edge of the reef. The lagoon, on the other hand, is generally less than 50 fathoms in depth, and in some atolls, as in that of the Kokos Keeling group, it is only from 2 to 7 fathoms deep.

Organisms of Oceanic Reefs. — Different organisms are generally found to grow in the lagoon and upon the outer slope of the reef. The latter, bathed by the cool, pure sea-water, rich in food particles, is the region of active coral growth, though a fringe of the nullipore, *Lithothamnium* (Fig. 189), generally occurs here. In the lagoon, lime-secreting sea-weeds (*Halimeda*, etc., Fig. 190)

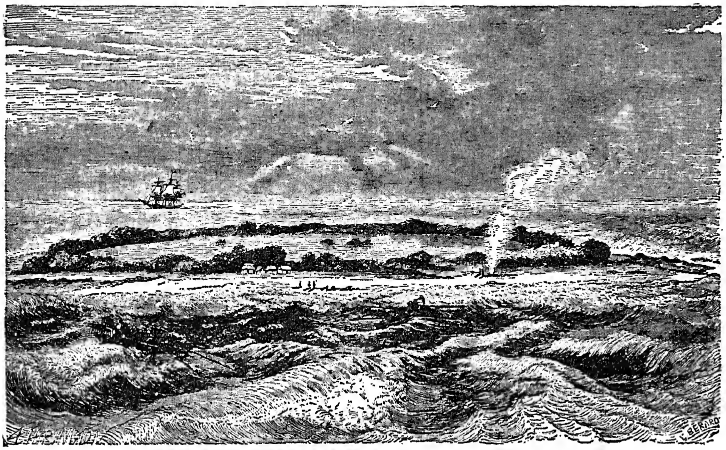


FIG. 220. — Whitsunday Island, a typical Atoll in the Pacific. (After Guyot.)

are generally abundant. Corals also grow there, being commonly of the more delicate branching forms, though others more common on the outside of the atoll are also represented. Some lagoons become gradually filled up by the growth of these organisms, while others seem to retain their depth and perhaps increase it and widen the lagoon by solution.

Theories of the Origin of Oceanic Reefs

No special theory is needed to account for the formation of a fringing reef, for it can be readily understood that coral polyps and other lime-secreting organisms which attach themselves to the submerged slopes of an oceanic island will in time build up a reef which fringes the coast of that island and rises nearly to sea-level, followed in many cases by the formation of islands upon it. The case is different, however, with the barrier reefs and the atolls, for here the lagoons must be explained, as well as the fact, that the reefs seem to arise from depths too great for normal reef-building corals to grow.

Several theories have been proposed for the explanation of such conditions.

The Subsidence Theory. — This theory was first proposed by Charles Darwin from his study of oceanic coral islands. It was later amplified and elaborated by the American geologist, James D. Dana, and has received its most recent support from the studies of the American physiographer, William Morris Davis. In general, this theory postulates that regions of barrier reef and atoll formation, are regions of subsidence. Beginning as fringing reefs in moderate depths upon the submerged slopes of oceanic islands which are

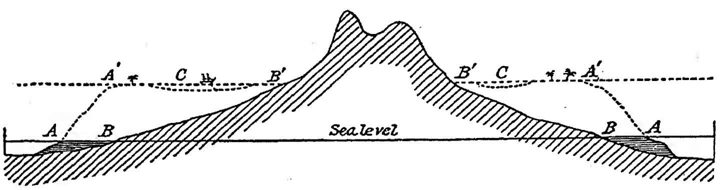


Fig. 221. — Diagram illustrating the conversion of a fringing into a barrier reef by subsidence. (After Darwin; from Vaughan.) *AA*, Outer edge of the fringing reef at the level of the sea; *BB*, shore line of the island at this stage; *A'A'*, outer edge of the reef after its upward growth during a period of subsidence and the formation of a new sea-level indicated by the dotted line; *B'B'*, the new shore of the encircled island; *CC*, the lagoon-channel between the reef and the island.

slowly sinking, the reefs grow upward and to some extent outward, the region of the greatest growth being the seaward margin of the reefs. Subsidence diminishes the diameter of the island, and a retreat of its shore-line from the original contact with the reef takes place, so that a constantly widening lagoon is produced between the reef and the island shores (Fig. 221). As Davis has pointed out, were it not for comparatively rapid subsidence, the mechanical débris washed from the island itself, during its destruction by the weather, would fill up the lagoon, whereas, in the most typical examples of such lagoons, the amount of visible mechanical sediment from the island is far less than would be expected from the extent to which the island has suffered erosion. Most of this sediment is submerged beneath the waters of the constantly widening lagoon. By continued sinking of the island and the corresponding upward building of the reef, the circular lagoon increases in size, until, when the last peak of the island has disappeared, the ring of water becomes closed into a central continuous lagoon, bounded

only by the circular reef upon which islands are built by waves and wind, and the atoll is complete (Fig. 222).

Such a theory of origin postulates the existence, among the oceanic reef-surrounded islands, of examples of all stages in this process, from those in which the fringing reef has only recently been built, to those in which the reef forms a well-defined barrier at a distance from the coast, with central islands of old rock of all sizes, from those of great extent and height to mere rocky peaks at the center of an almost perfect atoll. For it is evident that all the islands of

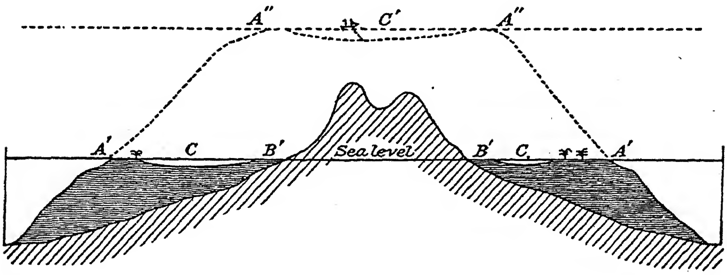


FIG. 222. — Diagram illustrating the conversion of a barrier reef into an atoll. (After Darwin; from Vaughan.) The barrier reef is closely shaded, the lettering corresponding to that of Fig. 221. The dotted lines represent the upward growth of the reef as the island subsides, and the new sea-level is represented by the dotted horizontal line. *A''A''*, the outer edge of the reef which forms the atoll; *C'*, the lagoon of the atoll, the depth of which on this scale is exaggerated, as is also that of the lagoon channel *C*.

an area did not have the same height or slope of surface at the time of the formation of the initial fringing reef. Therefore, even if the subsidence were uniform over wide areas, which need not at all be the case, some islands would disappear earlier than others, and some lagoons would widen more rapidly than others, because of the gentler slope of the surface of the rocky mass. This is illustrated in the following diagram (Fig. 223). Similar conditions would be produced in the case of islands of the same height and slope, but located in regions which were undergoing subsidence at different rates. Moreover, this theory requires that dead reef-building corals should be found in the position of growth at depths vastly greater than that normal for the growth of corals, for it is evident that as subsidence goes on, the older parts of the reef, formed in waters of 25 or 50 fathoms, will be carried downward with the sinking of the islands which support these reefs. These

conditions are satisfied, for not only are all gradations from fringing reefs to perfect atolls found among the oceanic islands and reefs, but a boring in one of the atolls, that of Funafuti in the Ellice Island group in the western Pacific, has shown the presence of these corals at a depth of over a thousand feet.

The chief objection urged against this theory of origin is the necessarily widespread subsidence of the ocean bottoms to carry down so many of the islands in such widely distant regions. Further, it is pointed out that in some of these island groups where barrier reefs and atolls would indicate subsidence, there is evidence of actual elevation at some points where the old coral reefs have been raised to a greater or less extent above the sea, so that in some cases the actual foundation upon which the reef was built has become exposed.

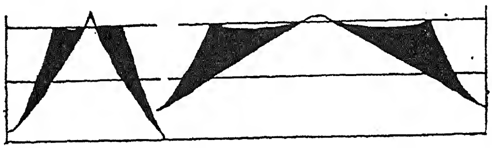


FIG. 223. — Diagram of two islands, showing varying amounts of submergence with the same rate of subsidence, due to variation in slope. The reef-deposits formed on the submerging slopes are shown in black. Note the more rapid increase in the width of the lagoon in the island on the right.

The Theory of Stationary Levels and Upbuilding of Reefs. — The English oceanographer, Sir John Murray, following an older suggestion of the poet-naturalist, Adelbert von Chamisso, and of the naturalist, Carl Semper, proposed a different explanation of the phenomena, and this has been further amplified and extended by the American oceanographer, Alexander Agassiz. These investigators started with the fact that corals will begin to grow wherever a submerged ridge rises to within the proper distance of the sea-level (25 to 50 fathoms), whether any portion of this is exposed above the sea as an old island or not. Such a ridge may be of volcanic origin, it may be an old island which has been worn down by the waves until it has largely or entirely disappeared, or it may be a submarine bank built up by the accumulation of shells and other organic structures until it has reached the proper elevation. When the coral masses growing upon such a foundation approach the surface of the sea, the centrally located individuals will die for lack of food and proper water conditions, while on the margin of the

mass, where the open sea-water bathes the corals, growth is vigorous. Fragments broken by the waves from this margin will roll down the seaward slope, and in time build the submerged platform outward, after which the coral polyps, etc., will take possession, and the margin of the reef is widened by outward growth. Meanwhile the dead coral masses on the inside will undergo solution by the waters rendered acid by the decaying organic matter, and a lagoon is dissolved out, the latter also increasing in diameter as the coral ring spreads on the outside. In this manner an atoll of any size may be produced from an originally solid reef of smaller size, while a fringing reef around an island would gradually move away from it by outward growth and the space between it and the island would widen by solution and scouring out of the lagoon channel.

Among the objections to this theory may be mentioned the fact that many lagoons are very wide, up to thirty miles or more, and also very deep, some having a depth of 200 feet. This would require an enormous amount of solution and removal of lime carbonate from the lagoon, were this produced from originally solid reef masses inside of the growing ring. Moreover, the lagoons of atolls are generally becoming filled by the growth of lime-secreting seaweeds, by the accumulation of foraminiferal shells and of other organic products, and by precipitation of lime through bacteria and other agents. While this theory may explain certain cases, it does not seem applicable to the problem as a whole.

Theory of the Rise of the Ocean Surface.—The German physiographer, Albrecht Penck, has proposed the theory of a rising sea-level which has been more fully amplified by the American geologist, R. A. Daly, though suggestions along this same line were made previously by others (T. Belt, 1874; W. Upham, 1878, etc.). It is known that in a period preceding that in which the modern barrier reefs and atolls were formed, an enormous ice-cap covered the northern portions of America and of Europe and a similar ice-cap covered the Antarctic regions. Such ice masses would exert an attraction upon the waters of the ocean which would, in consequence, flow toward them, lowering the sea-level in the equatorial regions throughout the world to a corresponding degree. The normal depth at which coral polyps could flourish at that time in the equatorial regions could, therefore, be much below that possible for them at the present time. As the ice melted the sea-water would

be returned, raising the level, and the additional water from the melting ice would increase the volume. During this continued rising of the sea-level the coral reefs, beginning as fringes around the islands, would grow upwards, while the central islands would become more and more submerged and some would finally disappear. Thus barrier reefs and atolls would be formed, the character and size of which would depend on the area and height of the original island or submerged platform. According to Daly's estimates, the amount of lowering of the sea-level at the beginning was from 200 to 230 feet, and this would also be the extent of the subsequent rise of the water-level. Hence the maximum depth of lagoons would be indicated by these figures, while the thickness of the entire reefs built during that time would range from that amount to that plus 150 to 300 feet, the original depth at which the corals began to grow. These requirements are borne out by many facts known concerning the reefs, but they do not apparently account for all of them.

Complex Origin of Reefs. — It seems likely that most or all of the factors here indicated are operative in the formation of coral reefs, and that some barrier reefs and atolls may originate in one way and others in another. Each group must be investigated by itself, and probably no single theory accounts for all the phenomena observed in such reefs in different parts of the oceans.

Epicontinental Reefs

Reefs which form in shallow water, either on the continental platform of the open ocean, or in the more or less enclosed bodies of water which form indentations into the land, are classed as epicontinental reefs, or reefs built upon the submerged portions of the continents. The best-known modern examples of reefs of this type are the Great Barrier Reef of Australia and the reefs of the Florida coast. Both are built up on the continental platform and have been extended nearly or quite to the seaward edge of that platform.

Great Barrier Reef of Australia. — This great complex of reefs extends, with a few interruptions, for 1250 miles, from Torres Strait in 9.5° S. latitude to Lady Elliott Island in 24° S. latitude. At Cape York the seaward edge of this reef is nearly 90 miles distant from the coast, and it descends to a depth often exceeding 1800 feet. This edge represents a great submarine wall or terrace which

fronts the whole northeast coast of Australia (Fig. 224). It rests at each end in shallow water, but near the center rises from great depths. The surface of this reef-complex forms a great plateau or platform, regarded by some as a submerged land surface, which is covered by from 10 to 30 fathoms of water, and is studded all over with steep-sided, block-like masses, the individual reef mounds, which rise up to low-water level (Jukes-Browne). These individual reef mounds are especially abundant along the outer edge of the bank or platform where they are bathed by the pure ocean water.

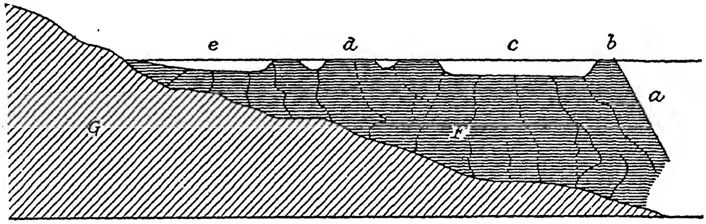


FIG. 224. — Diagrammatic section across the Great Barrier Reef of Australia. (After J. B. Jukes; from Vaughan.) *a*, Sea outside the Barrier, generally unfathomable; *b*, the actual barrier; *c*, clear channel inside the barrier, generally about 15 or 20 fathoms deep; *d*, the inner reef; *e*, shoal channel between the inner reef and the shore; *F*, the great buttress of calcareous rock formed of coral and the detritus of corals and shells; *G*, the mainland formed of granite and other similar rocks.

This linear series of reefs is the true barrier, but the submerged platform in some places extends beyond it. It is breached by narrow passages, and at rare intervals by navigable ship canals. The main part of the reef consists of coral heads and fragments bound together into a solid, hard mass, with the living coral polyps covering the outer surfaces. Most common among these are great masses of the irregular coral, *Porites* (Fig. 213), and the brain coral (Fig. 214). These, torn from their anchorage by the waves, are rolled about and worn, while at the same time they grind down the living and dead coral masses of the reef into fine coral sand and powder. Rolled and worn fragments of such corals, six to eight feet in diameter, are common on the outer slope of the reef, and they furnish an illustration of the manner in which the reef is worn away by the action of the waves. The coarser sand is washed into the channels, while the finer sand is carried seaward and settles on the bottom in deeper water. The material dredged here has the appearance of an impalpable, pale olive-green mud. which is wholly soluble in

diluted hydrochloric acid, thus showing that it is pure carbonate of lime. When dried it has the character and consistency of chalk.

Inside the barrier is a clear and broad channel, generally from 15 to 20 fathoms deep. The bottom is covered with unconsolidated lime-sand, ground from the reef, or with sand largely composed of the shells of Foraminifera (*Orbitolites*) which in places constitute the entire sand mass around the coral islands and the neighboring shores. Beyond the channel lie the inner reef mounds, which are separated one from the other by narrow water ways through which the tide rushes with great force. Such tidal currents may continue in the same direction, sometimes for two or three days, especially after great storms, and they form important agencies in the distribution of the lime-sand and mud.

The reefs of the inner series are peculiar in that many of them are composed chiefly of one kind of coral or other lime-secreting organism. Thus the Organ-Pipe reef of Thursday Island consists largely of the organ-pipe coral (*Tubipora musica*), while another reef is chiefly formed of the blue coral (*Heliopora cœrulea*). There are reefs largely made up of the hydrocoralline *Millepora* (Fig. 217), and others composed in large part of gorgonias. The inner reefs are separated from the mainland of Australia, which is formed of older rock, by a shallow channel which is mostly free from coral growth.

The Florida Reefs. — These arise from a shallow platform parallel to the southern margin of the peninsula and at a variable distance from it (Fig. 225). The southern coast of the peninsula rises from 12 to 15 feet above the sea-level, in the form of a curving ridge, and behind it lies the great fresh-water swamp of the Everglades, the surface of which is only two or three feet above sea-level (see section, Fig. 226). This rim has been regarded by Agassiz and Le Conte as marking the line of an older series of reefs behind which, on the site of the present Everglades, lay a lagoon which has since been converted into the fresh-water swamp. More recent investigation, however, has shown that this interpretation is probably not correct, though there are Tertiary coral reefs at Bainbridge, Georgia, and Tampa, Florida (Oligocene), and reef corals occur in the Pliocene (Caloosahatchie). From five to fifteen miles outside of the southern rim of the peninsula lies a line of small islands, the "Keys," which vary from less than four (Key West) to fifteen miles in length in the largest. These Keys have a gentle north-

ward slope and a steep southward or seaward face, and they clearly represent a line of extinct reefs upon which waves and winds have built up the islands. The channel between the Keys and the present mainland is very shallow; its floor is covered with fine silt, which at low tide forms exposed mud-flats rich in decaying organic matter. Many small, low mangrove islands dot the channel, and the aërial roots of the mangroves form a tangle where they enter the water, and this is very effective in checking the tidal currents and

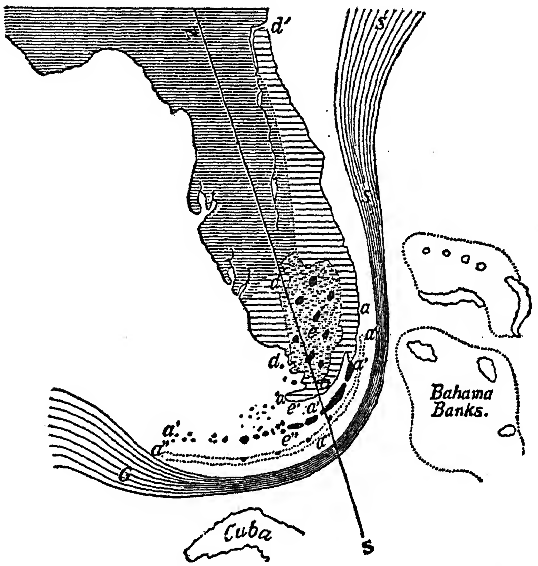


FIG. 225. — Map of Florida, showing the Keys and reefs. (After Le Conte.) *aa*, southern coast; *a′a′*, Keys; *a″a″*, living reef; *e*, Everglades; *e′*, inner channel; *e″*, outer or ship-channel; *GSS*, Gulf Stream.

forcing them to deposit their load of silt. In this silt are buried the remains of marine animals which have migrated from the open sea, and terrestrial and fresh-water forms which have come from the land. Also there are forms especially adapted to muddy bottoms, and their remains are mingled with the other types.

Outside of the line of Keys, and from three to fifteen miles distant from it, is the line of living reefs which is still, for the most part, submerged, and consists of a chain of reef mounds formed in part by corals (*Madrepora*, *Porites*, etc.) and in part by nullipores (*Corallina*, *Lithothamnium*, etc.). The channel between the living reef and the dead one (the Keys) is from five to six fathoms deep

and its floor is covered by coral-sand, shells of marine organisms, and oölitic lime precipitated by the agency of bacteria. These deposits are bedded, and when consolidated, will form stratified limestones. In some sections the delicate branching coralline seaweeds grow in abundance, covering the floor of the channel with a carpet of " country grass " as it is called. The dead portions of these corallines disintegrate into small fragments, and in places these form the main deposit on the channel floor.

On the outer or seaward side, the reefs slope steeply, and the sea-bottom quickly descends to great depth (2916 feet). The sweep

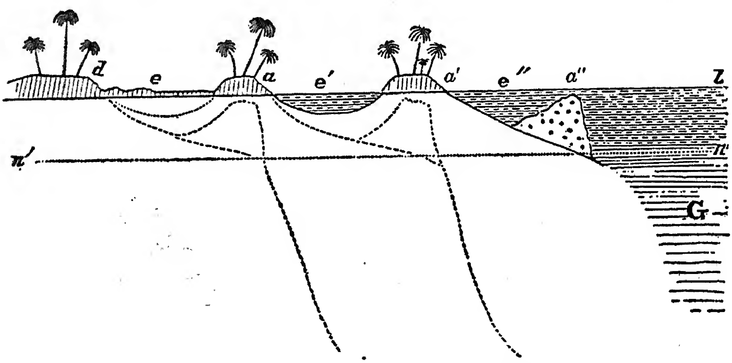


FIG. 226. — Diagrammatic section of Florida along the line *N. S.* in Fig. 225, showing the relative position of the south shore, *a*; Keys, *a′*; and living reef, *a″*; with the Everglades, *e*; the inner channel, *e′*; and the outer or ship-channel, *e″*; *n′n*, ancient submarine platform. The dotted lines indicate hypothetical former conditions. (After Le Conte.)

of the Gulf Stream here prevents any further southward extension of the deposits. These relationships are shown in the diagrammatic section along the line N. S. of the map (Fig. 225) given in the preceding figure (Fig. 226) and the details of the northern end of the reefs in the map (Fig. 227).

It is not difficult to see that we have here a succession of reef lines built seaward one after another, and that the older reefs became extinct and were converted into islands (the Keys) after the new line of reef was built, and so shut off the food-bearing currents from the inner reefs. In the outer channel, between the modern reefs and the Keys, lime deposits only are forming. This was also the case in the inner channel between the present Keys and the mainland, when the Keys were the outermost living reefs. After they became extinct by the building of the new reefs, the lime deposits

of the inner channel were covered by silts and muds, with much organic material. This would happen to the lime deposits of the outer channel if the outer or modern reef became extinct and were

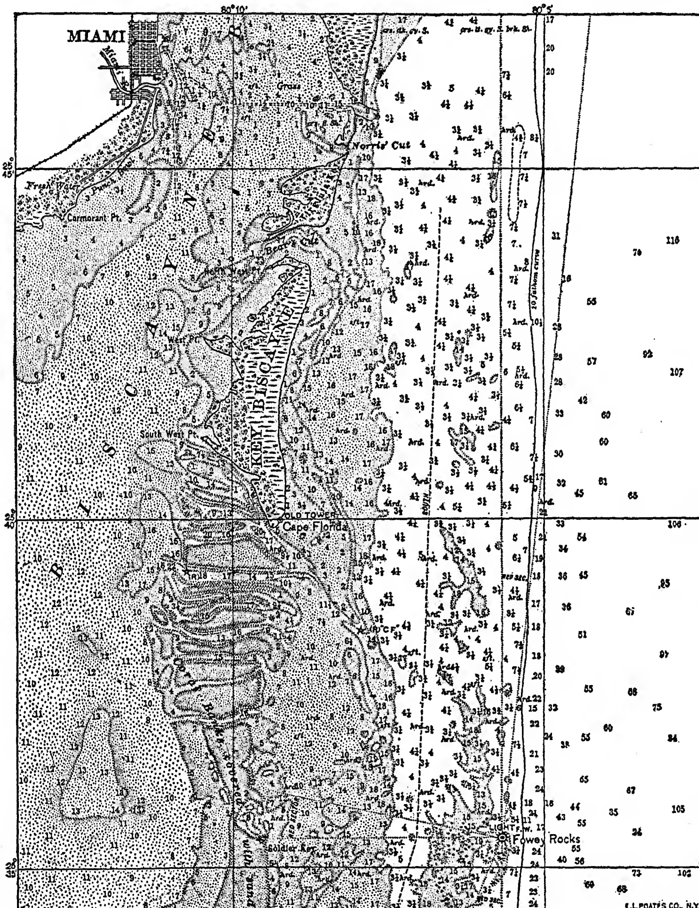


Fig. 227. — Chart of the northern end of the Floridian Barrier-reef. From United States Coast and Geodetic Survey, Chart No. 165. (After Vaughan.) The depths are given in fathoms. Note the sudden drop of the bottom outside of the 10-fathom line.

converted into islands. On consolidation of these deposits, the bedded limestones beneath would be covered with a mud rock or shale, probably of black color, on account of the abundance of decayed organic material in it. If the southern rim of Florida were an an-

cient line of reefs, it would represent the later stage in development to which the present Keys advance, namely the formation of a continuous belt of land. The Everglades have been regarded as a later stage in the silting up of the channel and its conversion into a fresh-water swamp in which deposits of decaying plants form the initial steps in the formation of a coal bed. Although this interpretation of the Florida rim appears not to be correct, it can be regarded as a possible stage in the gradual modification of such lines of reefs. The black mud which covers the limestone may, in turn, be covered by a coal bed, above which other deposits, such as wind-borne sands, etc., may accumulate.

Structures Common to All Reefs

It is important that we should understand the main structural features which distinguish reefs of corals and other lime-secreting organisms from other types of lime deposits, so that we may have definite means by which we can recognize older limestone deposits as due to reef growth, if such be their origin. In the first place, then, it should be noted that the main mass of the reef-mound is

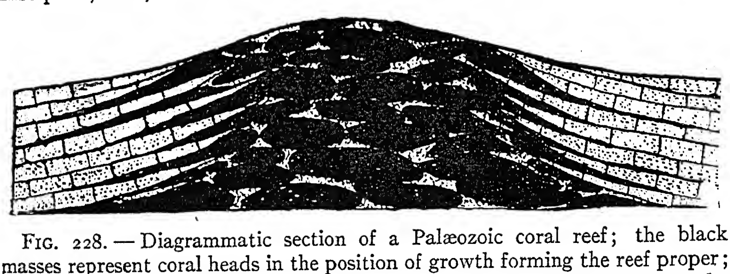


Fig. 228. — Diagrammatic section of a Palæozoic coral reef; the black masses represent coral heads in the position of growth forming the reef proper; around the margin are deposits of coral-sand and mud with steep dips near the reef where the edges of the reef and the coral-sand interfinger. (After Grabau, *Principles of Stratigraphy*.)

composed of coral or coralline structures *in the position of growth*. That is, as each new coral head or coral branch developed, it remained attached to the older dead coral mass or to the original rock-floor which served it as a foundation. Thus, in general, such a mound represents a mass of undisturbed coral and coralline structures. As the growth is not uniform, however, in all directions, numerous large and small cavities exist among the coral masses, and these cavities are generally occupied by shell-bearing and other animals whose hard parts remain there on the death of the creature. The lime-sand and lime-mud into which the waves grind the exposed corals is washed into these cavities, which may eventually be filled up by such material. On the margin of the reef, especially on the outer one, many coral heads and branching forms are broken from their anchorage and rolled about by the waves, grinding into sand and mud the coral masses over which they are rolled. When finally they themselves

become embedded in the coral sand, they are no longer perfect, but are broken and worn, and they may come to lie in all positions, being even completely overturned. The fine coral-mud resulting from the grinding will be carried out to deeper or quieter water, though it may also be caught in protected cavities within the reef. The coral-sand remains in shallow water to form bedded deposits.

Along the margins of the reef-mounds the bedded deposits of coral sand will often lie at a steep angle, which is sometimes as high as 45° or even more. Frequently a layer of small corals will grow upon such a bedded deposit, and this in turn may be covered by other lime-sands. Thus an interfingering of the organic lime structures, the corals, etc., with the clastic lime, the coral-sand, will result, and this is one of the most characteristic features of the margins of the reef-mound (Fig. 228).

Ancient Coral and Coralline Reefs

In the older limestone rocks of the earth's crust we often meet with structures which indicate that parts of these limestones were old reefs similar to those described, while the remainder of the limestone forms bedded deposits of coral sand or shell and nullipore fragments, etc., similar to those deposited to-day between lines of reefs. Not infrequently the corals of the reefs are distinctly recognizable, but in some cases they have been so altered in the course of time that they form a compact, structureless mass. When such a mass, devoid of bedding planes, and showing, in sections, more or less of a mound-like form, is enclosed by bedded limestones, which near the mound have a steeper inclination away from it in all directions, and when, furthermore, these bedded lime-deposits alternate with projections from the mound, it is generally safe to regard such a mass as an ancient coral or coralline reef. As has been said, however, many of these ancient mounds still show their coral or other organisms in perfectly recognizable condition, and in that case there can be little doubt of the reef origin of the mass if the structural characters above outlined are shown.

Silurian Reefs of Wisconsin. — Such a line of old reefs, composed largely of Stromatopora with some corals, was formed in ancient Silurian time in Wisconsin and adjoining areas. It has been traced for over sixty miles in length, and extended parallel to the old shore-line of an interior sea and at some distance from it. In general, it was formed under conditions not unlike those found to-day in the Great Barrier Reef. Many of the old reef-mounds have been opened in quarries near the city of Milwaukee and elsewhere, and though the mounds are mostly massive, the presence of the Stromatoporas can be recognized on the weathered surfaces of the quarry walls. The bedded lime deposits on the flanks of these mounds commonly show steep dips.

Silurian Reefs of Gotland. — Another series of such reefs was formed during the same period, parallel to the Swedish coast, in a sea which occupied the area of the present Baltic, and extended far east into Russia. Much of this reef series has been worn away, but a part remains to form the present Island of Gotland, and around the coast of this island, where the modern sea has cut cliffs, many beautiful sections of these reefs are exposed and their structures are well shown.

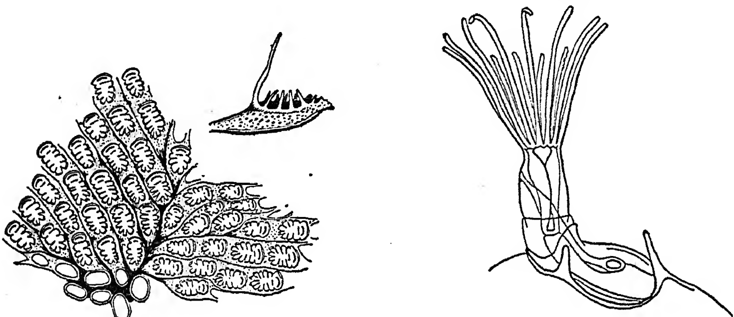
Devonian Reefs of the Eastern United States. — At a later period (Middle Devonian) a series of reef-lines, similar to those of the Florida coast, formed in the great interior sea which then covered much of North America. These reefs began as a line parallel to the eastern coast, which was formed by a land mass lying between this interior sea and the Atlantic Ocean, approximately along the line of the Older Appalachian Mountains. After the formation of the first line of reefs, a second one came into existence some miles farther to the northwest, and the old channel between the first reef-line and the mainland became silted up with carbonaceous muds. When a third and a fourth line of reefs appeared, each farther to the northwest, where the open sea of that time lay, the older channels were progressively silted up, and as streams brought mud and sand from the mainland of that time (on the southeast), the old extinct reefs themselves were covered by muds and sands. Several of these lines of reefs have been definitely located. One passes through eastern New York and Pennsylvania, another passes under the city of Buffalo, a third under northern Ohio, and a fourth, the last formed of the series, through northern and western Michigan. While this last line of reefs was forming, the older reefs on the southeast were being buried under heavy layers of mud and sand. Many of these reefs show the characteristic structures in a striking manner, as one passes from one quarry-opening to another. The corals which enter into the construction of these reefs are, of course, very different from those found in modern reefs. The chief types were the honeycomb coral (*Favosites*, Fig. 216) and various star corals (*Prismatophyllum*, *Craspedophyllum*, etc.). Tube corals (*Syringopora*) and Stromatoporas also abound, the latter often of very large size. Besides these there were many simple horn-shaped corals and other organisms as well. On the margins of the mounds, where the bedded lime-sand deposits dip away from the reef, many broken and worn coral and Stromatopora fragments are found embedded in the sands, lying in all positions.

Triassic Reefs of the Dolomites. — Many other reefs of this kind are found in various parts of the world, and some of these will be again referred to in the later part of this book. We must note here only one other example, which appears to represent an ancient reef of the oceanic type. This is a mass of dolomitic limestone, about 3000 feet thick, which now forms the famous peaks of the Dolomites in the Alps of the Tyrol (Fig. 4, p. 9). These limestones were formed in the Triassic period of the earth's history and are largely composed of the remains of nullipores, though other reef-building organisms also occur. The limestone is massive and without structure except around the margins, where the interfingering character, so typical of reefs, is shown. The surrounding deposits of which this reef-like mass formed a part are of the bedded type of clastic material.

OTHER LIME-DEPOSITING ORGANISMS

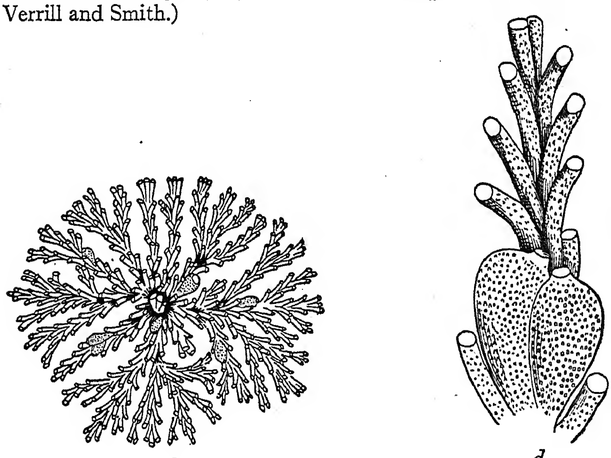
Bryozoa and Limestones Formed by Them

The Bryozoa are chiefly marine animals of a higher grade of organization than the coral polyps, but they secrete structures of carbonate of lime, which in many cases are not easily distinguished



a *b*

FIG. 229 *a, b*. — A modern Bryozoan (*Membranipora pilosa*). *a*, a group of cells or zoœcia seen from above (enlarged), and a single cell seen from the side (still further enlarged); *b*, a single zooid expanded (much enlarged). (After Verrill and Smith.)



c *d*

FIG. 229 *c, d*. — Another modern Bryozoan (*Crisia eburnea*). *c*, a cluster of branches (enlarged); *d*, a single branch bearing ovicells and zooid cells (zoœcia) (much enlarged). (After Verrill and Smith.)

from corals, except by the trained student. Modern Bryozoa either incrust seaweeds, rocks, or other substances, or form delicate leaf-like but irregular expansions of carbonate of lime (Figs. 229 *a–d*).

Many ancient Bryozoa, however, built branching, often cylindrical masses, which were admirably adapted to the making of beds of limestone (Fig. 230). They more often grew in sheet-like associa-

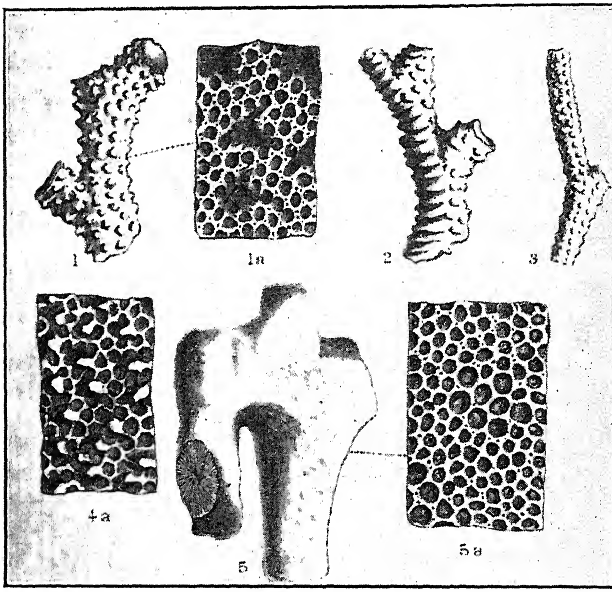


FIG. 230.—Group of rock-forming Bryozoa from the Ordovician (Cincinnati Group). 1, *Hallopora ramosa;* 1 *a*, enlargement of surface; 2, *H. rugosa;* 3, *H. dalei;* 4 *a*, *Dekayia aspera*, enlargement of surface; 5, *Hallopora andrewsi;* 5 *a*, enlargement of surface. (After Nicholson.)

tion on the sea-floor, but in some cases also formed reef-like mounds. Examples of the latter are shown in the cliffs cut by the Black Sea and the Sea of Azof on the coast of the Peninsula of Kertch (Crimea).

Shell-bearing Animals and Shell Limestones

There are two important groups of shell-bearing animals in the seas, the Brachiopoda and the Mollusca. The latter are represented by several classes, of which three are especially common in the sea to-day, the bivalves or pelecypods, the gastropods, and the pteropods. A fourth group, the cephalopods, was extremely abundant in former times, but is represented by only a few types to-day.

Brachiopods.—In this class the shell is composed of two principal parts or *valves*, one generally larger than the other, but each symmetrical about a median line drawn through the apex of the

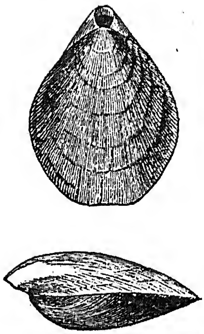


FIG. 231. — *Terebratulina septentrionalis.* A characteristic modern Brachiopod of the northern Atlantic coast. (From Binney and Gould.)

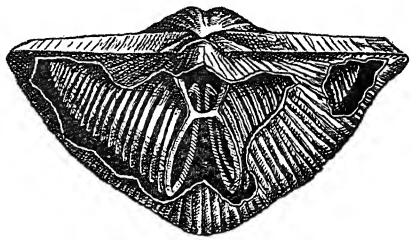


FIG. 232. — A Palæozoic brachiopod shell partly broken to show the internal spiral arm-supports. (*Spirifer striatus,* Sowerby.) Mississippian limestones. Note the symmetrical character of the shell with reference to a median line drawn through the apex or beak.

valve (Fig. 231). These animals were far more common in the older geological periods, especially those of the Palæozoic (Fig. 232), than they are to-day, and in the past they often formed beds of limestone largely, or almost entirely, composed of their shells. Some brachiopods (*Lingula* Fig. 233, *Obolus*) carry a high percentage of phosphoric acid and are an important source of lime phosphate.

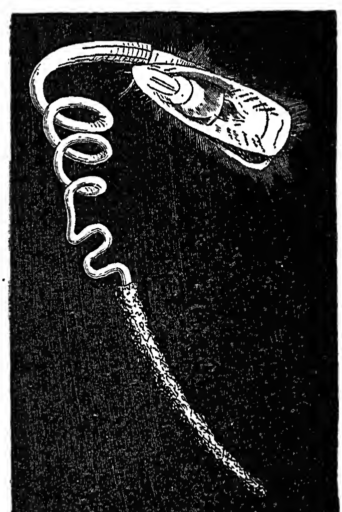


FIG. 233. — *Lingula pyramidata,* natural size. A deep sea brachiopod. (After Brehm; from Ratzel, *Die Erde.*) The shell of this animal contains about 55 per cent of phosphate of lime and magnesia.

Bivalves or Pelecypods. — In these mollusks (also called lamellibranchs) the soft body of the animal is enclosed by a shell of two valves which are generally similar, except in the oyster and some other types, forming the right and left valve respectively. Each valve, however, shows an asymmetry of form, a line drawn through the apex not dividing it into two equal portions. In this respect the pelecypod shell is readily distinguished from the brachiopod shell. Examples are

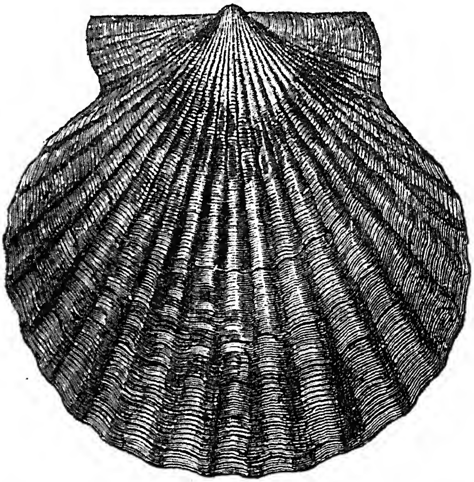


FIG. 234. — *Pecten irradians*, the common scallop of the Atlantic coast. (From Binney and Gould.)

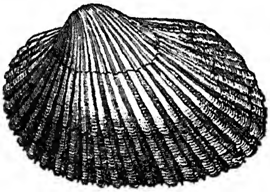


FIG. 235. — *Arca transversa*, a common plicated shell of the Atlantic coast. (From Binney and Gould.)

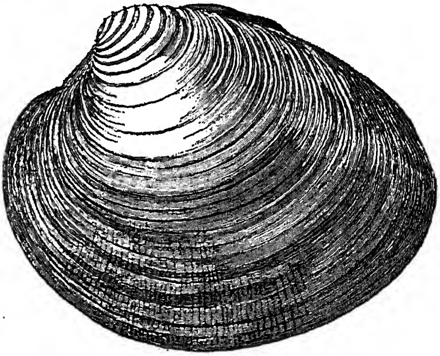


FIG. 236. — *Venus mercenaria*, the common quahaug or salt-water clam, about three fourths natural size. (From Binney and Gould.)

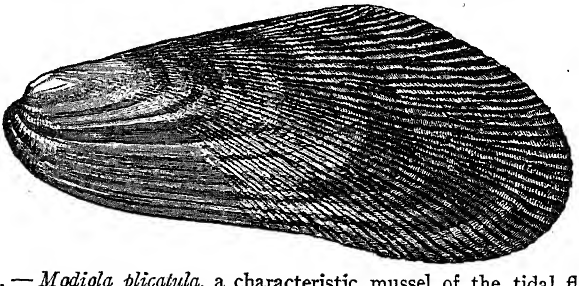


FIG. 237. — *Modiola plicatula*, a characteristic mussel of the tidal flats and salt-meadow streams of the Atlantic coast. (From Binney and Gould.)

the clam, scallop (Fig. 234), arca (Fig. 235), quahaug (Fig. 236), mussel (Fig. 237), etc.

Gastropods. — The second class, abundantly represented to-day, is that of the gastropods or snail-like mollusks, in which the shell is coiled in a spiral (Figs. 238–241). These shells are often highly colored and marked by various features such as ridges, nodes, spines,

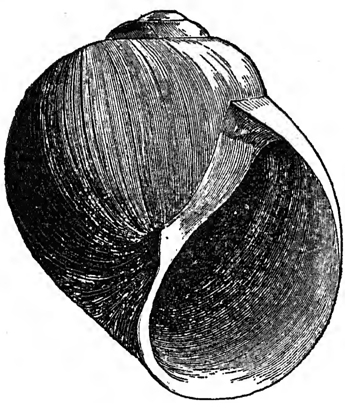


FIG. 238. — *Lunatia heros*, the common salt-water snail of the Atlantic coast. (From Binney and Gould.)

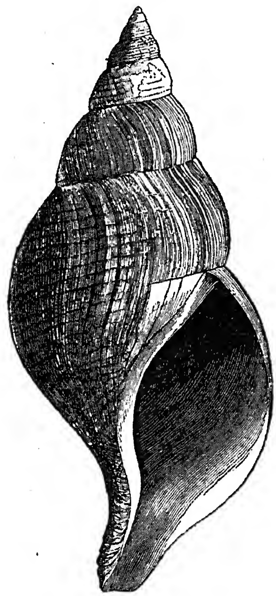


FIG. 239. — *Neptunea islandica* (*curta*). A common fusoid gastropod of the northern Atlantic; three fourths natural size. (From Binney and Gould.)

and the like. Both pelecypods and gastropods have formed limestone beds in the past. On the coast of Florida such shell limestone is forming to-day, where shells and fragments of them are washed into protected areas, remaining long enough so that the percolating waters may deposit lime between them and bind them together. This rock is locally called coquina (Fig. 242).

Pteropods. — A third class of shell-bearing mollusks is that of the pteropods, so-called because a part of their body (the foot) develops into wing-like appendages. These animals float in vast numbers upon the surface of the ocean, the shell-less species (Fig. 243) serving as an important article of food for the whalebone whales.

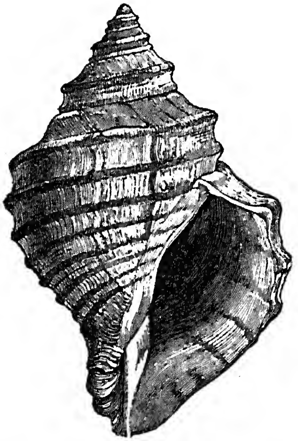


FIG. 240. —*Chrysodomus decemcostatus.* A characteristic fusoid gastropod of the northern Atlantic; three fourths natural size. (From Binney and Gould.)

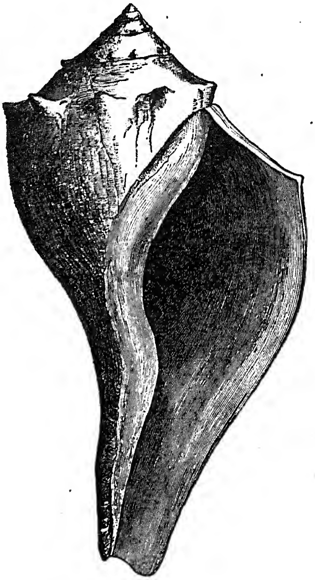


FIG. 241. — *Fulgur carica*, a characteristic gastropod of the Atlantic coast from Cape Cod to Florida; one half natural size. (From Binney and Gould.)

FIG. 242. — A piece of modern shell-limestone or *Coquina* from the Florida coast; somewhat reduced. (Photo by B. Hubbard.)

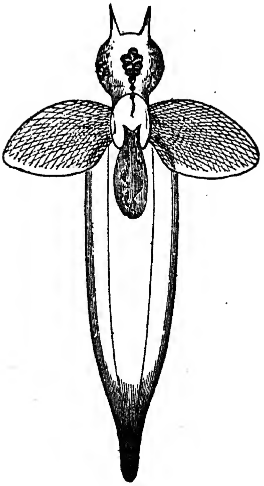
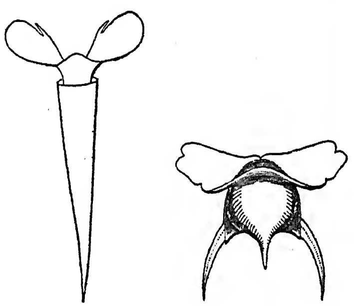


FIG. 243. — *Clione limacina*, a modern shell-less pteropod; enlarged twice. (From Binney and Gould.)

In correlation with their floating habit, the shell, when present, is thin and light, and often quite transparent (Figs. 244 *a*, *b*). Such shells accumulate in vast quantities upon the sea-bottom in regions where the animals abound in the surface waters, and of them is formed a deep-sea pteropod ooze (Fig. 245). Limestones made entirely of shells of such animals, though not necessarily of deep-sea origin, are found in our older geological series. One of these,



a *b*

FIG. 244. — Modern shell-bearing pteropods. *a*, *Styliola vitrea*, about two and one half times natural size; *b*, *Cavolinia tridentata*, approximately natural size. (After Verrill and Smith.)

FIG. 245. — Deep-sea pteropod ooze, enlarged 16 diameters. (After Murray and Renard; from Grabau's *Principles of Stratigraphy*.)

found in New York State, carries on the average 40,000 shells to the cubic inch (Fig. 3, p. 8). This limestone may have been formed by the rapid settling of millions of these animals which were killed by being driven into the mouths of estuaries of that period. Where the remains of organisms of this kind abound in rocks which are of shallow-water origin, they may often be the source of important petroleum deposits, as will be more fully shown in the next chapter.

Cephalopods. — This group is to-day represented chiefly by the *Nautilus* (Fig. 246) and by a number of shell-less types (squids, Fig. 247; cuttle-fish, Fig. 248; octopus, etc.). During the Mesozoic era, however, there lived a great group of such shelled cephalopods, the *Ammonites* (Fig. 249), which in some cases were so abundant that they built up beds of limestone, while in other cases

FIG. 246.—The modern Pearly Nautilus (*N. pompilius*); the animal occupies the living chamber of the sectioned shell. (After Owen; from Woodworth.) *a*, mantle; *b*, dorsal fold; *e*, nidamental gland; *g*, shell-muscle; *iii*, siphon; *k*, funnel or hyponome; *n*, hood; *ooo*, exterior digitations; *p*, tentacles; *s*, eye; *xx*, septa; *z*, last or living chamber.

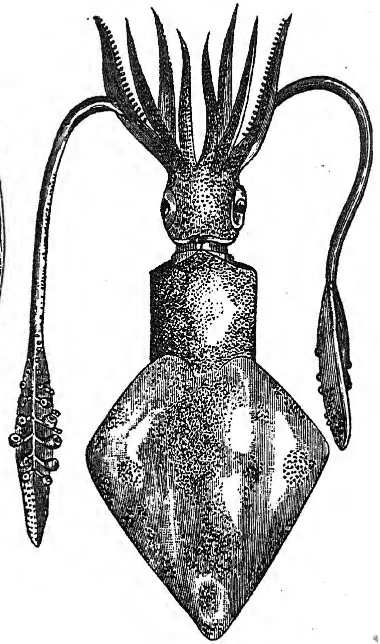


FIG. 247.—The Squid (*Loligo vulgaris* Linn.). A modern decapod cephalopod with remnant of internal shell only.

FIG. 248.—Cuttle fish "bone" (*Sepia officinalis* Linn.). Internal shell (much reduced). The fine point at the base of the structure represents the *guard* of the Belemnite, the main mass corresponds with the *proöstracum.*

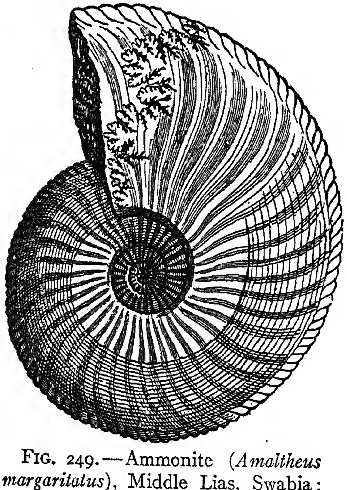


FIG. 249.—Ammonite (*Amaltheus margaritatus*), Middle Lias, Swabia; side view. Where the shell has been partly worn away near the aperture, the complex "suture line" is shown.

they constitute the chief source of the calcareous substance of the rock. In the Palæozoic era other types similar to the modern Nautilus, and also straight, conical or gently tapering shells, the orthoceran type (Fig. 250), occurred in great abundance, and

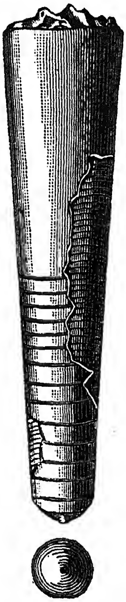


FIG. 250.—A simple straight-shelled cephalopod. (*Orthoceras tumidum*, Barr.) Silurian of Bohemia; two thirds natural size. Where the shell has been removed, the straight "sutures" are shown. The position of the central tube or "siphuncle" is seen in the bottom view. (After Barrande.)

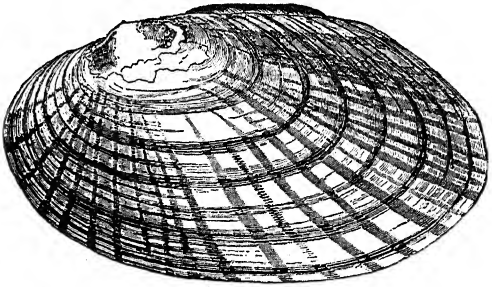


FIG. 251. — *Unio radiatus*. A common species of fresh-water clam, of New England ponds and streams. (From Binney and Gould.)

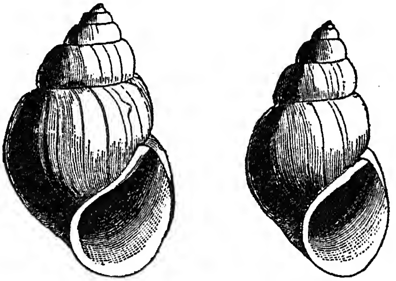


FIG. 252.—*Paludina decisa* var. *integra*. A characteristic snail of fresh-water ponds. Female on left, male on right. (From Binney and Gould.)

were an important source of lime of many rocks, sometimes forming their chief constituent (Orthoceras limestone).

Fresh-Water and Land Mollusks

In fresh water, too, deposits of limestone are formed from the shells of bivalve and gastropod Mollusca. Among the former, the great fresh-water clam (*Unio*, Fig. 251) is the most important, and among the latter, the pond snails (*Paludina* or *Vivipara*, Fig. 252)

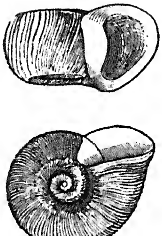


FIG. 253. — *Planorbis trivolvis*, a common pond and river snail. Side and bottom views. (After Binney and Gould.)

FIG. 254. — *Limnæa elodes*. A common snail of stagnant ponds. (From Binney and Gould.)

FIG. 255. — *Physa heterostropha*, the common species of left-handed snail of brooks and ponds. (From Binney and Gould.)

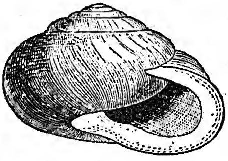


FIG. 256. — *Helix albolabris*, the common garden snail. (From Binney and Gould.)

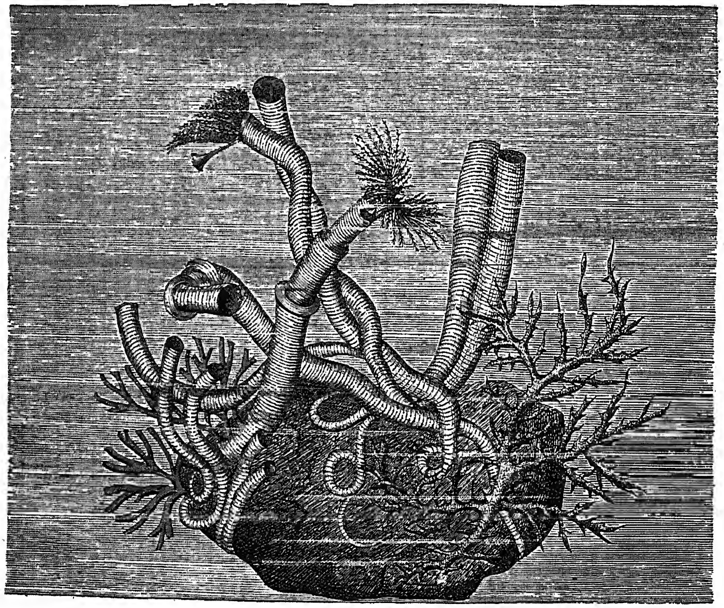


FIG. 257. — *Serpula contortuplicata*, slightly reduced. Two of the tubes show the expanded fringe of the animal. (From Ratzel, *Die Erde*.)

and the river snails (*Planorbis*, Fig. 253; *Limnæa*, Fig. 254; *Physa*, Fig. 255). More commonly, however, these form impure deposits of marly rock mingled with much mechanical sediment. The common snail (*Helix*, Fig. 256) lives upon moist land, but the shells may be washed into basins and so become an important constituent of limestones.

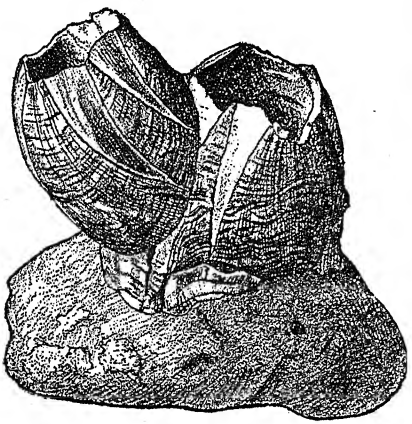


Fig. 258. — The Barnacle (*Balanus*). Type of fixed crustacean, one half natural size. (After Haug.)

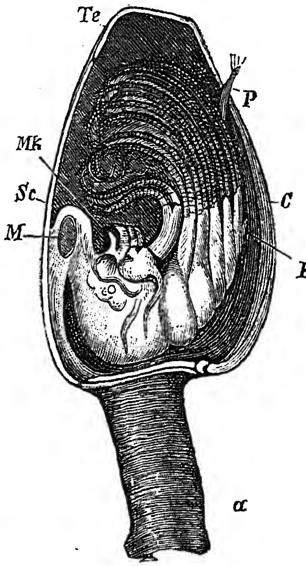


Fig. 259. — The modern ship- or goose-barnacle (*Lepas*). After removal of the right valve. *a*, stem; *C*, *Te*, and *Sc*, shell pieces; *C*, *carina; Te, terga; Sc, scuta; Mk*, mouth; *F*, furca; *P*, cirrus (or penis); *M*, muscle. (From Haas, *Leitfossilien.*)

Worms and Crustaceous Animals as Limestone Formers

Worms. — A small number of marine worms build calcareous tubes in which they live. These tubes often form a dense mass which may become at times important as a limestone former; *Serpula* is an example (Fig. 257).

Crustacea. — This class is best known from its modern representatives, the lobsters, crabs, crayfish, and the very aberrant barnacles (Fig. 258), and the goose-barnacle, *Lepas* (Fig. 259). None of these ever occurs in such abundance as to form rocks, but a peculiar class, the *Ostracods* (Fig. 260), in which the animal secretes a bivalve shell, in form often like that of a small bean, may be a rock-former. Some of these abound in the streams and ponds of localities in western

North America and elsewhere, and the accumulation of the shells gives rise to a calcareous fresh-water ooze which, from the prevalent form, is called *Cypris ooze.* Members of this class were also abundant in the ocean in various geological periods, and limestones largely composed of ostracod shells have been formed in the past.

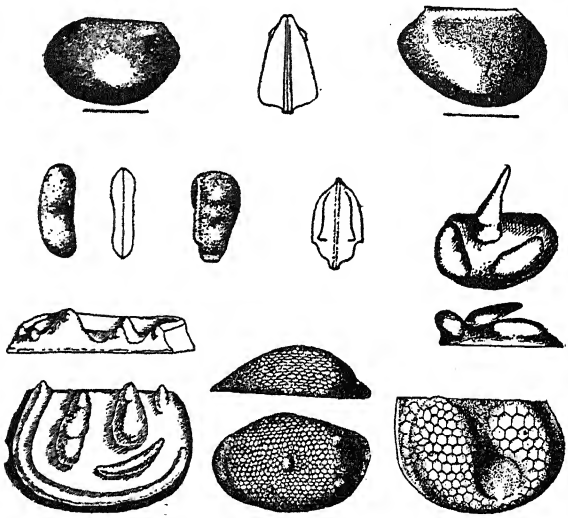


FIG. 260. — A group of fossil Ostracoda.

Upper row: *Leperditia angulifera* (Silurian).

Middle row; left to right: *Cytherideris impressa,* lateral and dorsal views ×20 (fresh-water Cretaceous, Bear River); *Cythere monticula,* lateral and dorsal views ×20 (Bear River Cretaceous); *Æchmina abnormis,* right valve side and (below) dorsal view ×10 (Rochester shale, Silurian).

Lower row: *Drepanella crassinoda,* right valve, side and (above) dorsal view ×10 (Ordovician); *Primitiopsis punctulifera,* left valve, side and (above) dorsal view ×18 (Hamilton-Devonian); *Primitia seminulum,* left valve ×18 (Hamilton, Devonian). (From Grabau and Shimer, *North American Index Fossils.*)

Finally, the remarkable extinct group of the *Trilobites* (Fig. 261), so-called because the body is divided longitudinally into three parts or lobes, often becomes an important source of lime in the Palæozoic era, and in Sweden some thin beds of (Cambrian) limestone are entirely composed of the calcareous outer coverings of these animals (Fig. 262). Crustacean structures contain up to 26 per cent of calcium phosphate and may be an important source of this substance.

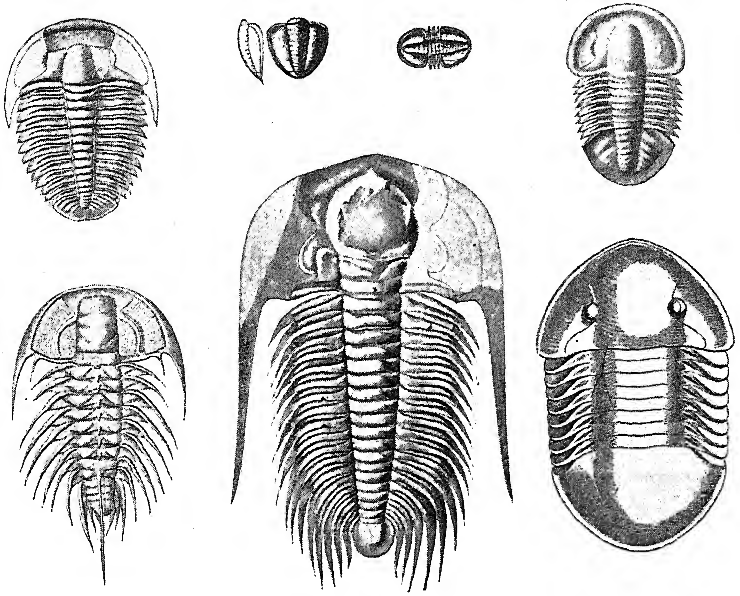


FIG. 261. — A group of Trilobites, the characteristic Palæozoic crustaceans.

Upper row: *Ptychoparia kingi*, Cambrian; *Microdiscus speciosus*, pygidium, side and surface views; (enlarged). The same, entire specimen, Cambrian; *Asaphiscus wheeleri*, Cambrian.

Lower row: *Zacanthoides typicalis*, Cambrian, *Paradoxides harlani*, Cambrian, *Isoteles gigas*, Ordovician. (From Grabau and Shimer, *North American Index Fossils.*)

Crinoids and Crinoidal Limestones

Among the great division of spiny-skinned marine animals, the echinoderms, to which the starfish (Figs. 263, *a*, *b*) and sea-urchins (Figs. 263 *c*, *d*) belong, there is one group, that of the Crinoids (Fig. 264) and their relatives (Cystoids and Blastoids), which were important rock-formers in the past (Palæozoic and Mesozoic, Fig. 265). Crinoids live to-day in water of considerable depth, but in the Palæozoic era they appear to have been abundant in shallow seas. The animal has a cup-shaped body provided with numerous slender arms, and is

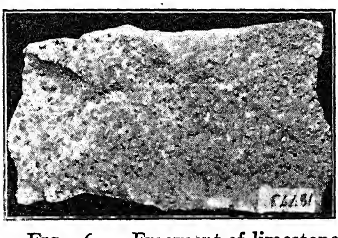


FIG. 262.—Fragment of limestone entirely composed of the remains of a small trilobite, *Agnostus*. Upper Cambrian, Sweden; one third natural size. (B. Hubbard, photo.)

affixed to the sea-bottom by a stem, often of great length. This stem is composed of a series of calcareous plates or disks, set one upon the other and held together by muscular tissue. When the animal dies, these disks fall apart because of the decay of the

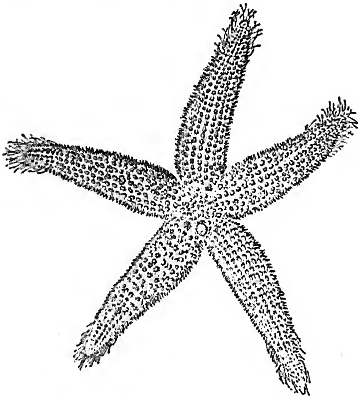


FIG. 263 *a*. — A common form of star-fish (*Asterias arenicola*), somewhat reduced. (After Verrill and Smith.)

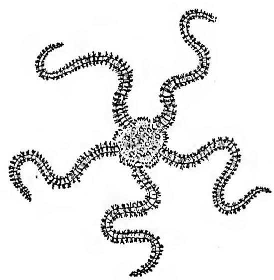


FIG. 263 *b*. — A common form of brittle star (*Ophiopholis aculeata*). Dorsal view, about one half natural size. (After Verrill and Smith.)

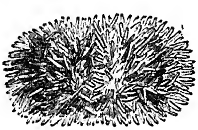


FIG. 263 *c*. — The common sea-urchin of the North Atlantic (*Strongylocentrotus dröbachiensis*). Side view, about half natural size. (After Verrill and Smith.)

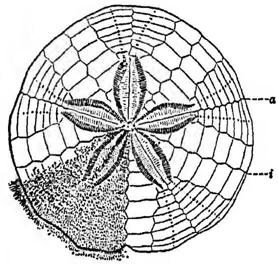
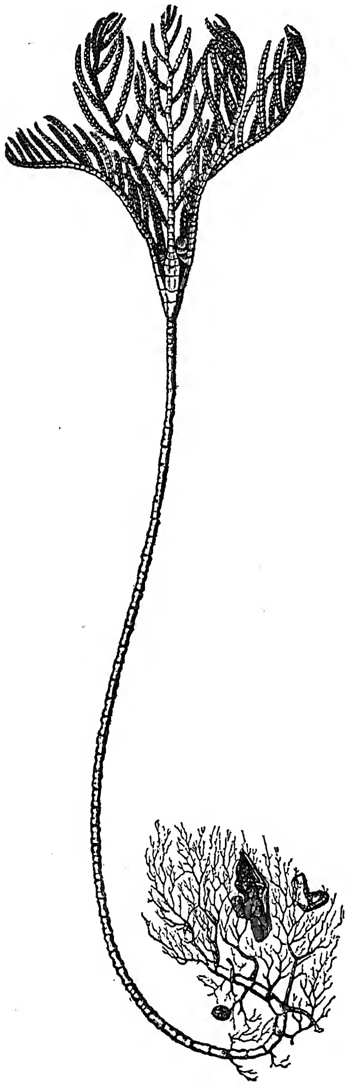


FIG. 263 *d*. — The common sand-dollar or flat sea-urchin (*Echinarachnius parma*). Upper surface with the spines partly removed, about five sevenths natural size; *a*, ambulacral zone; *i*, interambulacral zones. (After Verrill and Smith.)

muscular tissue, and they will then accumulate to form a bedded deposit of lime which may be many feet in thickness. The body and arms of the animal are also composed of calcareous plates which are added to the mass, but the stem disks are the most abundant and prominent. They form what is called a *crinoidal limestone*, readily recognized from the form of the disks (Fig. 266).



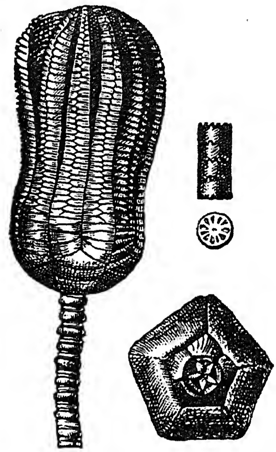


FIG. 265.—An extinct lily-crinoid. (*Encrinus liliiformis*, Lk.) Muschelkalk (Triassic). Reduced, with basal view of calyx and stem joints.

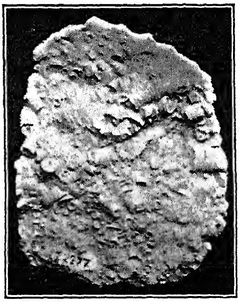


FIG. 264.—A modern crinoid (*Rhizocrinus loffotensis*) showing stem with "root" or hold-fast for attachment, and a crown composed of the calyx and branching arms. Slightly enlarged. (After Brehm; from Ratzel.)

FIG. 266.—A fragment of crinoidal limestone, or rock composed almost entirely of the stem-joints of crinoids. (Palæozoic.) About one half natural size. (B. Hubbard, photo.)

Accumulations of Bones of Vertebrates

The highest division of the animal kingdom, the vertebrates, secretes an internal skeleton which is composed of carbonate and phosphate of lime, and accumulations of such bones, either around salt licks or in ponds and other basins into which they are washed, may form important beds of limestone rich in lime phosphate. Where fish are suddenly killed in the sea, as by an earthquake or the sudden encroachment of cold waters after a storm, vast quantities of fish-bones may accumulate on the sea-bottom; or, where the sea enters a river estuary, the river fish may suddenly be killed by the salt water, and a deposit of their bones formed on the floor of the estuary. Such fish-beds are often found in the geological series, and they may be of local importance as members of the rock formation. Extensive deposits of bones of land animals are also found in caverns, and elsewhere, forming bone-breccias. Some of these will be referred to in later chapters of this book.

Organic Deposits of Phosphate of Lime

Phosphate of lime is probably, in most cases, of organic origin, but in the sea, where the source is chiefly the bones, teeth, and excrements of fish, and the shells of some phosphate-secreting animals (such as *Lingula* (Fig. 233, p. 309) among the brachiopods, and the Crustacea), secondary chemical deposition seems to occur to produce further phosphatization of the original deposits and to form the phosphatic nodules which are subsequently concentrated by weathering of the enclosing rock, until they form important deposits. Upon the land, accumulations of bones of animals may form a source of phosphate of lime, but by far the most abundant and striking deposits of this character are formed by the droppings of birds on islands and of bats in caves. These deposits are called *guano*, and they are common on many of the islands of the Pacific; they also abound in the West Indies and on the islands off the African coast. Indeed, such deposits of bird guano are almost universal around the ocean borders and on their islands. One of the most extensive occurred on the islands off the Peruvian coast, but this has been largely exhausted. In the past, guano formed an important source of commercial phosphate rock, but at present deposits of other origin (generally concentrated marine deposits)

are more frequently used. Bat guano is much less important and much less common than bird guano.

ORGANIC DEPOSITS OF SILICA

Organic silica is far more uncommon and less widespread than is lime of organic origin. Nevertheless, it becomes locally of much importance. Both plants and animals form deposits of organic silica, sometimes in fresh water, but chiefly in salt water.

Diatoms (Fig. 267). — These are plants of low organization belonging to the division of the algæ. They abound in both fresh and ocean water, being mostly of microscopic dimensions, and they are furthermore remarkable in that they commonly possess the power of locomotion. Within the body, which is a single organic

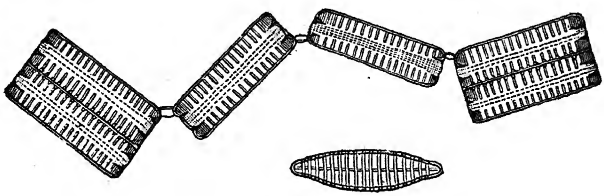


FIG. 267. — Modern diatoms (*Diatoma vulgare*, Bory). The individuals are joined in a zigzag band; much enlarged. (From Haas, *Leitfossilien*.)

cell, they build up a structure of silica, often of very beautiful form and of great variety. This structure, called the *frustule*, consists of two pieces which fit together like the body and cover of a pill box. In some fresh-water ponds they are so numerous that they form accumulations on the bottom of the pond, largely composed of these minute silicious bodies. A rock is thus formed which resembles chalk in consistency and general aspect, but which, unlike chalk, will polish metals or other hard substances. Such rock is called *diatomaceous earth* when impure and *tripolite* when pure (from a famous deposit of this material at Tripoli in north Africa).

A diatom ooze is also formed in the sea, especially in the Southern and Antarctic oceans, on the floors of which it is estimated to cover an area of ten million square miles, at an average depth of 1500 fathoms (see the map, Fig. 198, p. 277). In the northern part of the North Pacific, an area of about forty thousand square miles is also covered with diatom deposits. These deposits are generally not pure, but other silicious organisms (Radiolaria, sponge spicules) and earthy matter occur with them. Diatoms sometimes

form the chief element of rocks in marine deposits, not always of deep sea origin. If diatoms are carried by currents from the sea, into a more or less enclosed basin in which the waters are stagnant, or if they grow in such stagnant waters, they will accumulate in quantities upon the bottom, but as in such cases there are few animals which feed upon the organic matter of the diatoms, this will also accumulate and by decay form a hydro-carbon which saturates the deposits of silicious diatom shells, and may become an important source of petroleum and natural gas. Such deposits occur in the Tertiary series of rocks in California, and the great oil accumulations of these rocks are believed to have been derived from the organic matter of these diatoms which was retained in this deposit because of the peculiar conditions of formation.

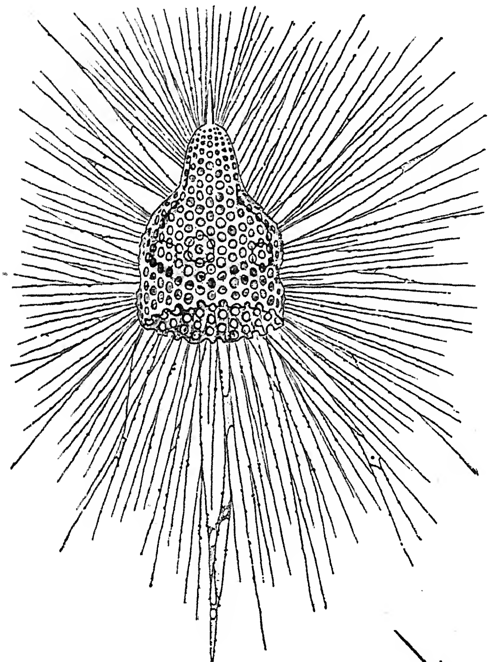


FIG. 268 *a.* — A modern Radiolarian, showing the skeletal structure of silica and the extended fleshy threads or pseudopodia (*Eucystidium cranoides*). Much enlarged. (From Haas, *Leitfossilien.*)

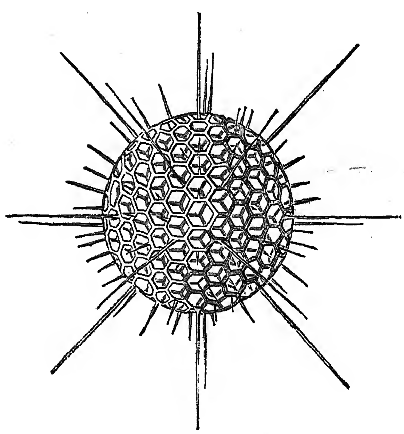


FIG. 268 *b.* — *Heliosphæra echinoides*, a modern Radiolarian. Greatly enlarged. (After J. Murray; from *Haug Traité.*)

Radiolaria (Figs. 268 *a*, *b*). — These are minute, single-celled animals related to the Foraminifera and with them forming the mineral-secreting members of the division of Protozoa. Unlike the shells of the Foraminifera, however, the hard structure secreted

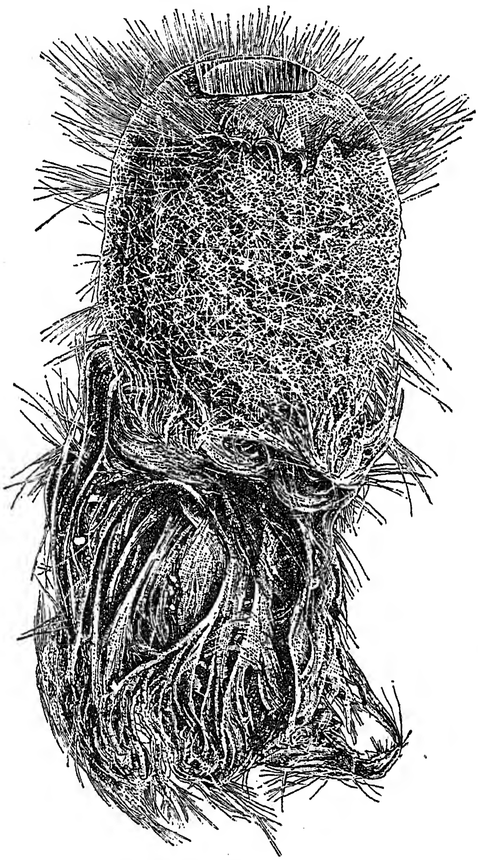


FIG. 269. — A modern sponge with silicious skeletal structure, and basal glass fibers for fixation (*Holtenia carpenteri* Thomson).

by the Radiolaria is internal and consists of a network of glass or silica of wonderful variety of form in the various species. These animals live only in the sea, and their shells accumulate in the greatest purity on the deeper portions of the sea-bottom, where foraminiferal shells are not found because they are dissolved before they reach that depth. Commonly there is, however, an

admixture of red clay, a very characteristic deep-sea deposit. When more than 20 per cent of the deposit consists of Radiolaria it is customary to speak of it as a radiolarian ooze. Radiolarian oozes are not known in the Atlantic, but occur in the deeper portions of the Pacific Ocean and in small areas of the Indian Ocean

FIG. 270.—A Cretaceous sponge with silicious skeleton retaining its form (*Ventriculites simplex.* Mantell.)

(see map, Fig. 198, p. 277). There is, however, a deposit now exposed on the island of Barbadoes in the Windward group of the Antilles, which is a typical radiolarian ooze with red clay, and appears to be an old sea-bottom deposit now uplifted.

Radiolaria are also found in shallow water deposits, where they become included in other sediments. They are not uncommon in the lagoons of coral reefs, and they have been found in the chert bands of older limestones formed in association with reefs. The chert bands themselves are often the redeposited silica derived from the solution of scattered Radiolaria and other silicious organisms.

Sponge Spicules. — Many modern marine sponges (Fig. 269) secrete within their soft, horny, and fleshy masses, minute needles of silica. These are set free on the decay of the sponge, and some-

times form an important source of silica in other deposits. Many of the sponges of former geological periods built solid structures

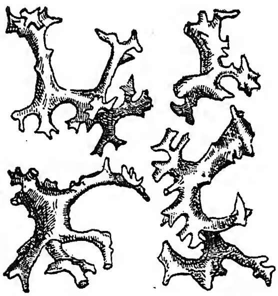


FIG. 271 *a*. — Isolated spicular bodies of an extinct silicious sponge. (*Epistomella clivosa*, Quenst. White Jura.)

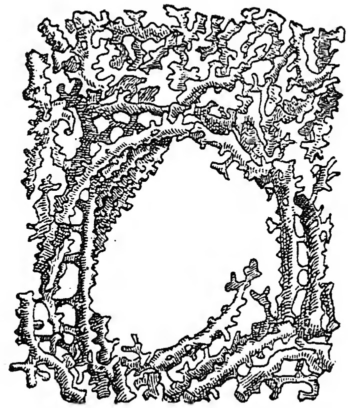


FIG. 271 *b*. — Part of the skeletal structure of a lithisdid silicious sponge. (*Jereiea polystoma*, Roem. Mucronaten-Kreide. Upper Cretaceous, Germany.)

by a union of such spicules (Figs. 270–271 *a*, *b*) and so became important sources of organic silica. The flint of the chalk (Fig. 162, p. 224) is believed to be largely derived from such sponge spicules.

CHAPTER XIII

THE ORGANIC OR BIOGENIC ROCKS: DEPOSITS FORMED FROM THE ORGANIC TISSUES OF PLANTS AND ANIMALS

Deposits Formed from Vascular Plants

Conditions and Processes of Decay

Under ordinary conditions, when a plant, whether herb or tree, dies, it soon decays, and practically nothing remains behind except a minute quantity of mineral matter. The plant tissues, which are composed of carbon, hydrogen and oxygen, chiefly in the form of the material called *cellulose*, unite with the oxygen of the air, partly through the activities of micro-organisms (bacteria), and carbon dioxide and water are formed. The same result is achieved more rapidly by the burning of the dry plant tissues, when, however, some unconsumed carbon may pass off as smoke. Slow decay under the atmosphere is, in effect, a very slow but complete burning of the tissues without the production of a flame or the development of easily perceptible heat. The reaction in either case is as follows:

$$\underset{\text{Cellulose, etc.}}{C_6H_{10}O_5} + \underset{\text{6 molecules of Oxygen}}{12O(=6O_2)} = \underset{\text{6 molecules of Carbon Dioxide}}{6CO_2} + \underset{\text{5 molecules of Water}}{5H_2O}$$

The carbon dioxide is a gas, and the water passes off as invisible vapor. If plants are burned where oxygen does not have free access, as in a charcoal oven or kiln, or under a covering of earth, the oxidation is incomplete, the hydrogen and oxygen escaping as water, while some of the carbon may also be converted to carbon dioxide; but the greater part of the carbon remains behind in the form of charcoal.

In like manner, when plants become submerged in the waters of a swamp or marsh, free access of oxygen is prevented and only partial decay will result. At first only a part of each of the com-

ponent elements will pass into the air in the form of gaseous combinations, the chief of these being carbon dioxide (CO_2), water (H_2O), and marsh gas, a combination of carbon and hydrogen (CH_4). As the change progresses, especially under pressure of other material which may be spread over the plant tissues, more of the oxygen and hydrogen will be eliminated, and the relative amount of carbon remaining will be progressively increased, though there is, of course, no actual increase in carbon, but rather some decrease. This forms the several series of coals. Finally, with the application of both pressure and heat, most or even all of the other substances may be driven off and pure carbon alone remains, producing graphite. In special cases crystallization of the carbon may result in the formation of diamonds.

Types of Vegetal Deposits and Stages in Alteration

Peat. — The first product of partial decay of vegetable matter is peat. According to the degree of decay and the character of the vegetable material, peat ranges in color from brown to black, and is a loose, spongy mass in which the structure of the vegetable tissue is only partly obliterated (Fig. 272). Peat forms only in stagnant waters, for here alone complete decay is arrested. This seems to be due to the fact that the bacteria which are active in the decay produce certain by-products which give to the stagnant water an antiseptic character, with the result that the bacteria are destroyed and the process of decay is arrested. Peat bogs are proverbial for their antiseptic qualities, and in them bodies of animals and of men are often preserved for long periods of time. If these by-products are removed, as in running or much agitated waters, the decay continues until it is complete.

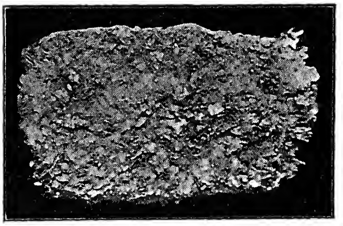


FIG. 272. — A fragment of peat — about one half natural size. (Photo by Hubbard.)

Types of Peat and Conditions of Formation. — The areas of peat formation, or the moorlands, may be either low-lying or they may be high moors. The former division comprises the shore moorlands or marine marshes, and the fresh-water swamps and

fenlands, the latter the upland bogs. These types will now be more fully considered.

Marine marshes. — Where the waves break on a gently sloping sandy coast, they commonly build up an off-shore or outer bar,

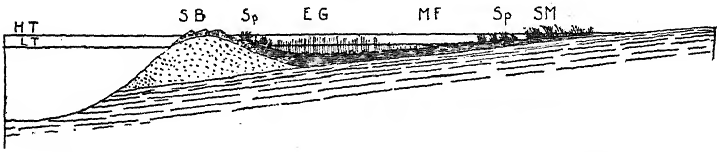


FIG. 273. — Diagrammatic section of an off-shore bar and the barachois or lagoon enclosed by it. *HT*, high tide-level; *LT*, low tide-level; *SB*, sand bar formed by waves from sea-bottom sand; *Sp*, marsh grass or *Spartina* zone; *EG*, eel-grass zone; *MF*, mud-flat, uncovered at low tide; *SM*, salt meadow, covered only at highest tides.

leaving a lagoon or *barachois* of protected water between it and the land (Fig. 273). This lagoon may be many miles in width, but is never very deep, seldom over 30 feet, and its waters are never

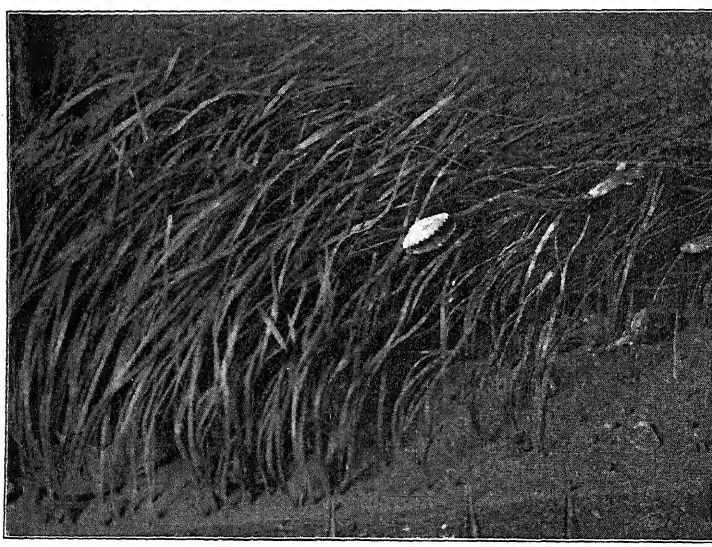


FIG. 274. — Eel-grass growing upon a muddy bottom, Woods Hole, Mass. (Photograph of part of foreground of reproduction of annulate group; by courtesy of American Museum of Natural History.)

completely cut off from the open sea, joining it either around the end of the bar or through narrow openings across it. In the quiet waters of the lagoon, where the depth is not over 12 feet, eel-grass

will begin to grow. This is a plant belonging to the pond-lily family, but adapted to live only in salt water (Fig. 274). Meanwhile the bar may be converted into a barrier beach by the formation upon it of sand dunes, heaped up by the wind from the sand of the bar, exposed and dried at low tide, and the deeper parts of the lagoon may slowly become silted up, after which, when the proper depth is attained, the eel-grass will spread over these parts. At low water the eel-grass will form a dense tangle which checks the tidal and other currents and forces them to deposit their load of

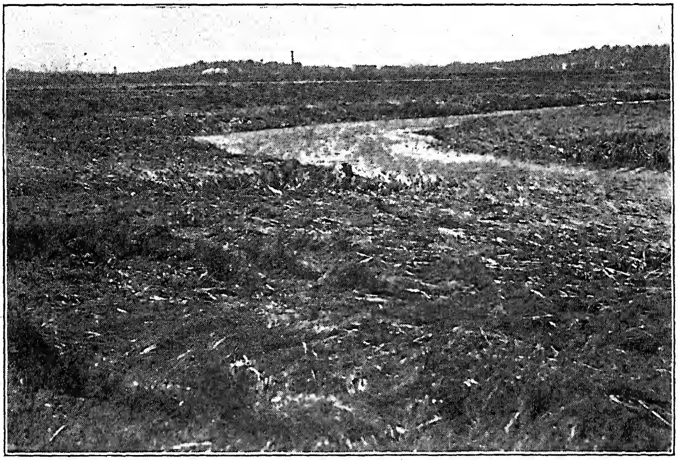


Fig. 275. — View of the salt meadows at Winthrop, Mass., showing the rank growth of salt thatch (*Spartina*) and the tidal stream dissecting the meadow.

silt, and thus further filling of the lagoon takes place, the silt accumulating around the eel-grass blades. When silting-up has progressed so far that at low tide parts of the bottom are exposed, the eel-grass there will die, and a mud-flat results, in which live clams and other marine organisms, and from which a fetid odor of marsh gas is evolved. Finally, the higher portions of the mud-flat are taken possession of by the marsh grasses (*Spartina*) and as these die down year by year, patches of peat are formed from their roots and decaying stems. As the growth of grasses spreads and the surface rises through the accumulation of the peat, other species of marsh grass, which can stand less submergence, will take possession and these will continue to build up the peat deposit. Finally the entire lagoon, or a large part of it, will be converted into

a salt meadow, which is submerged only at the highest tides, but which is intersected by numerous tidal channels, on the margins of which the peat can be observed at low water (Figs. 275, 276). Meanwhile the sand dunes, traveling inland under the influence of the winds from the sea, will begin to cover parts of the salt meadow, and the waves, cutting back the bar which they had originally formed, will eventually remove it, exposing the peat beds

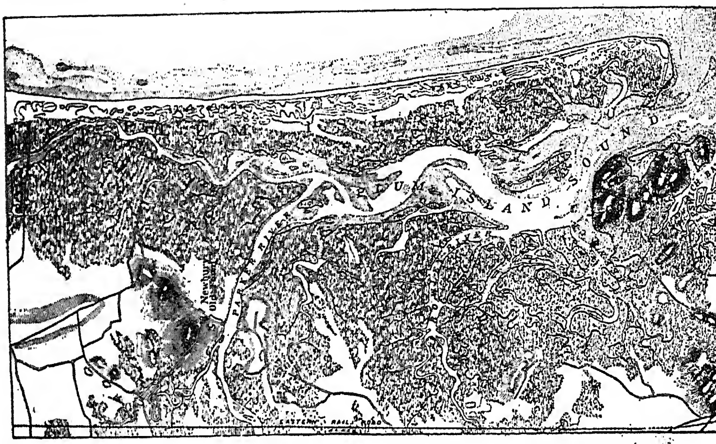


FIG. 276. — Map of the salt marsh near Newburyport, Mass., with Plum Island Sound and creek representing the remains of the lagoon; the sand bar is known as Plum Island. (After Shaler.)

upon the outer shore of the barrier beach, which is now formed of the sand dunes resting upon the peat beds of the old lagoon. Unless a change of level occurs, the cutting process of the waves will eventually again destroy the entire series of deposits which have formed in the lagoon. Hence such accumulations are not generally of a permanent character, though special conditions may occur to preserve them. Where, however, a rock barrier separates an old lagoon from the sea, as in parts of the northern New Jersey meadows, the opportunities for preservation of the peat deposits are more favorable.

Deposits of peat formed in salt meadows are never very thick, unless the coast is slowly sinking as the peat grows, and at a corresponding rate. On the Massachusetts coast, where such subsidence has taken place, peat deposits composed of the remains of high-tide vegetation have been found to have a thickness of 20 feet. Upon the southern Atlantic coast the average thickness is probably not much over four feet, though this would vary with the

magnitude of the tides. Many variations occur, dependent on the original condition of the coast, and it may even happen that salt-water peat, formed only of the taller marsh grasses, will overlie a fresh-water peat which was formed before the sea encroached over that area owing to slow subsidence of the land or other causes. Examples of such complex deposits are found on the Massachusetts coast.[1] Salt peat is almost always rich in silt, which is brought in by the tides or in fine sand and dust which is blown there by the wind. Moreover, the contact of the salt water with the decaying vegetation favors the activities of certain bacteria which will decompose the sulphates in solution in the sea-water, and cause the formation of sulphureted hydrogen (H_2S),

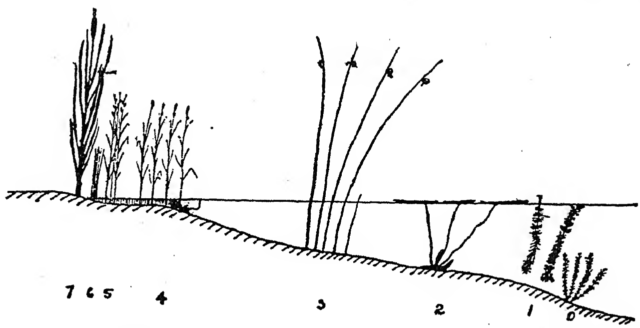


Fig. 277. — Diagram of plant zones in small lake near Merryman's Lake, Michigan. (After C. A. Davis.) 0, Chara; 1, floating bladderworts; 2, yellow pond-lily; 3, lake bulrush; 4, Sartwell's sedge; 5, bottle sedge; 6, spike rush; 7, cat-tails.

a characteristic product of the salt meadows, easily recognized by its odor. This will react upon the iron compounds in the silt, and finely divided iron sulphide (the mineral pyrite) will form. If then in time such salt peat is converted into coal, that coal will be high in ash, because of the silt, and will be rich in sulphur minerals, especially iron pyrites. When formed in the normal way above outlined, such a coal should rest upon mud and sand beds which contain the remains of marine organisms, and the coal itself may contain such remains, since shell-bearing Mollusca and other animals, such as crabs, are not uncommonly found in peat deposits of this origin. On the Atlantic coast the shells of the plicated mussel (*Modiola plicatula*, Fig. 237, p. 310) are especially abundant in the peat beds. Some of the plants found in these salt meadows are shown in Fig. 278 *a*.

Swamps. — Many small lakes are converted into swamps by becoming choked with vegetation, or the margins of larger ones may become swampy through similar causes. In general, we may distinguish two types of plant deposits in lakes, — that formed by algæ and that formed by the so-called vascular plants, that is,

[1] See further Grabau, *Principles of Stratigraphy*, p. 492. Johnson, *Shore Processes*, p. 385.

those that have a regular structure like or resembling that of wood, and which include all the plants from mosses and ferns up. Algæ abound in fresh as in salt water, each habitat having its own species and genera. As the algæ may occupy all parts of the lake waters, the deposits formed by their dead tissues will cover the lake floor in a more or less continuous layer, provided there are no bottom animals to feed upon them. Mingled with these algæ are the pollen grains of trees such as the conifers which grow in the neighborhood, while fresh water diatoms also accumulate. This material will form a homogeneous, structureless mass, more or less mingled with fine sediments, with the calcareous particles from the stone-worts (Chara) (Fig. 192, p. 273) which grow under such conditions, or with the silicious frustules of diatoms (Fig. 267, p. 323). Such a mixture of decaying organic material with mineral matter is called a *sapropelite*, and according to the amount of impurities present, it becomes, on compacting, either an oil shale, or when nearly pure, a cannel coal. The pure

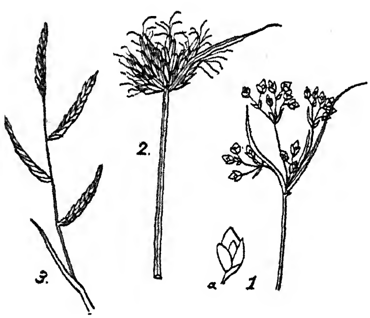


Fig. 278 *a*. — Salt marsh plants; enlargements of the flowing portions, by which they are chiefly distinguished. 1, a rush, *Juncus gerardi*, northern salt marshes; 2, bulrush, sedge family, *Scirpus americanus*, common on borders of salt and fresh ponds and streams; 3, rush salt grass, *Spartina junca*, salt marshes. (From drawings by Mary Welleck.)

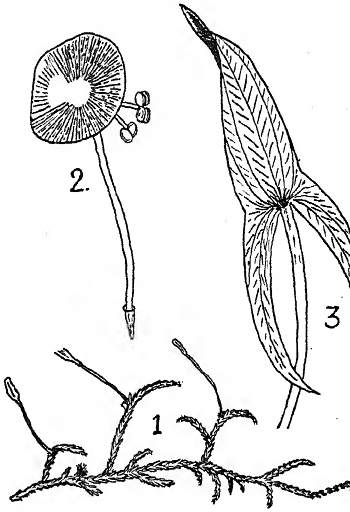


Fig. 278 *b*. — Characteristic swamp plants taking part in peat-forming. 1, a common peat-moss, *Hypnum*, $\times 1\frac{1}{4}$; 2, common duckweed, *Lemna*. The entire plant is reduced to a leaf-like expansion which bears a long slender root and small flowers; forms green floating scum on ponds and stagnant pools, $\times 8$; 3, a leaf of arrowhead (*Sagittaria*), a member of the water-plantain family, growing abundantly in swamps. One fourth natural size.

decaying organic slime is called *sapropel*. (*Sapros*, σαπρός = rotten, *pelos*, πέλος = mud.)

The peat of the lake-swamps, on the other hand, is formed from vascular plants (Figs. 277–279). In the deeper waters of many of

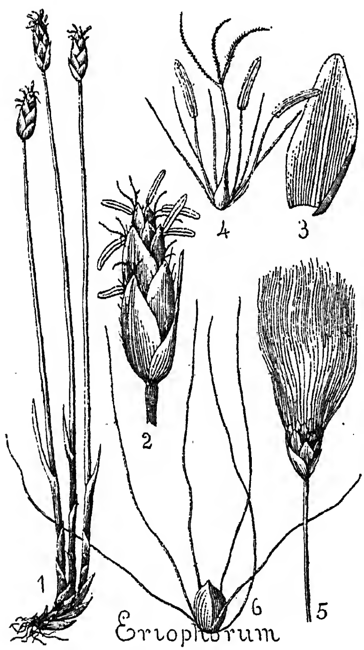


FIG. 278 *c*. — Cotton grass (*Eriophorum alpinum*), a member of the sedge family. 1, small entire plant; 2, spike; 3, a single scale; 4, a flower from the same; 5, a spike in fruit, the bristles forming a cottony tuft; 6, a single one-seeded dry fruit or achenium, with bristles — much enlarged. A characteristic peat plant in cold bogs, northern United States and Europe. (After Gray.)

FIG. 278 *d*.— The twig-rush (*Cladium mariscoides*), a characteristic plant of the bogs of the northeastern United States. 1, summit of plant; 2, detached spike; 3, the same opened, showing a staminate and a perfect flower; 4, the nut-like fruit or achenium; 5, longitudinal section of the same. (2–5 enlarged; after Gray.)

our lakes, pond-lilies form the chief vegetation, these rising from depths not exceeding 25 feet. Next come the reeds, such as bulrushes, cat-tails, flags, water plantain, arrowheads (Fig. 278 *b*3), some grasses, and the wild Indian rice (*Phragmites*, Fig. 278 *f*), most of these not growing well in water more than two feet deep. Be-

sides these, there are floating plants such as the bladderwort and the duck-weed (*Lemna*, Fig. 278 b_2), which may cover large surfaces as with a green carpet. Near the shore, sedges (*Carex*, Fig. 278 *e*) and peat-mosses (*Hypnum*, Fig. 278 b_1) appear, and these may form a floating mat of entangled plants which extends from the shore outward often for a considerable distance, and because of the interwoven roots and branches makes a buoyant structure capable, in its thicker portion, of supporting considerable weight, but dangerous to enter upon in its outer thinner parts (Fig. 280). The peat formed from such a mat grows in thickness year by year, as the under part suffers partial decay and compacting, and new growth takes place on top, and thus the margins of the lake gradually become filled in by a zone of peat which progressively extends toward the center of the lake. Outside of the zone of sedges and peat-mosses appears the zone of water-loving trees, such as the alders and the tamarack in the northern, and the cypress and tupelo in the more southern regions, and in the shadow of these grows a rich assemblage of ferns, sedges, horsetails, and the peat-moss, *Sphagnum*. As the mat thickens, these trees will advance over it, growing now upon the site of the former lake margin, which is converted into a "quaking bog." If Sphagnum is present, this will often grow to such an extent as to cover

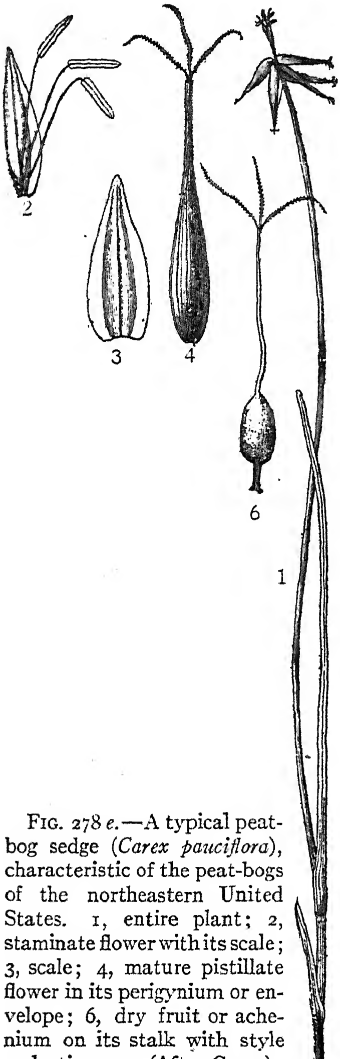


FIG. 278 *e*.—A typical peat-bog sedge (*Carex pauciflora*), characteristic of the peat-bogs of the northeastern United States. 1, entire plant; 2, staminate flower with its scale; 3, scale; 4, mature pistillate flower in its perigynium or envelope; 6, dry fruit or achenium on its stalk with style and stigmas. (After Gray.)

the lower parts of the trunks of the trees, and keeping them moist, will cause their death. As the trunk breaks off above the covering of moss, the stump or "stool" remains and is covered by the growing moss, as are also the fallen trunks. A mass of

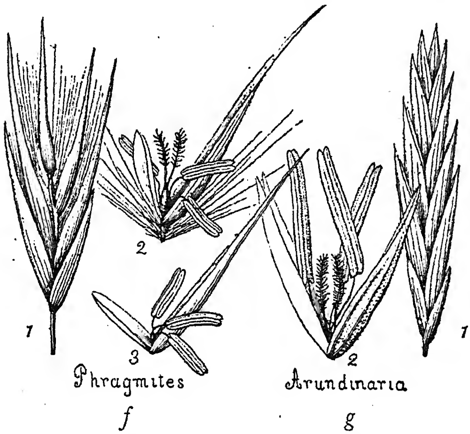


FIG. 278 *f* and *g*. — Flowers of Reed and Cane: *f*. the common reed, *Phragmites* (*Arundo*) *communis*, of the American and European reed swamps, growing from 5 to 12 feet high with leaves 2 inches wide (see Fig. 279). 1, spikelet enlarged; 2, one of the perfect flowers enlarged; 3, lowest flower with stamens only. *g*. The large cane (*Arundinaria macrosperma*), which forms the cane brakes of the southern states. It grows from 10 to 20 feet in height with leaves 1 to 2 inches wide. 1, a spikelet; 2, a separate flower magnified. (After Gray.)

FIG. 279. — Reed zone (*Arundo phragmites* zone) on the border of the high moors. The trees in the background, especially *Pinus silvestris*, are smaller here than in the intermediate moor. (After Potonie, *Die Entstehung der Steinkohle.*)

peat of variable character is thus produced, carrying in its upper part stools and fallen tree trunks, leaves, ferns, etc., and resting near the center of the lake upon a deposit of sapropelite. The

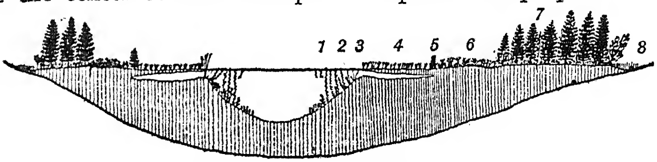


FIG. 280. — Diagram showing how plants fill ponds from the sides and top. 1, zone of Chara and floating aquatics; 2, zone of pond weeds or Potamogetons; 3, zone of water-lilies; 4, floating sedge mass; 5, advance plants of conifers and shrubs; 6, shrub and Sphagnum zone; 7, zone of tamarack and spruce; 8, marginal fosse. (After C. A. Davis.)

thickness of the deposit is determined in part by the depth of the lake and by other causes. If covered by sediments, such a peat deposit may be preserved and subsequently compacted into coals. Such conditions for preservation are best found on broad river

FIG. 281. — Southern margin of Dismal Swamp 12 miles west of Elizabeth City, N. C., showing general aspect of swamp in the month of May. (Photo by Russell, from U. S. G. S.)

flood-plains or on the great flat alluvial plains near their mouths. Here not only exist all the conditions which favor the formation of swamps, but at intervals the rivers, charged with sand and mud, may spread this over and cover the peat deposit and so preserve it. Borings in river deltas, such as that of the Ganges and others, have

revealed successive deposits of peat at various depths, covered by and alternating with sands and muds, and in a condition suitable for conversion into coal.

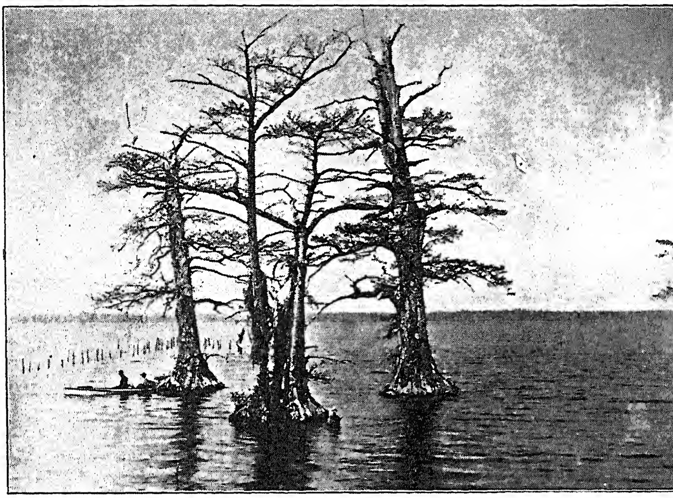


FIG. 282. — Cypress trees in the eastern part of Lake Drummond, Va. (Photo by Russell, from U. S. G. S.)

FIG. 283. — A swamp in Florida.

Examples of our largest swamps in which peat is forming to-day are Okefenoke Swamp in Georgia, 50 miles from the sea and 115

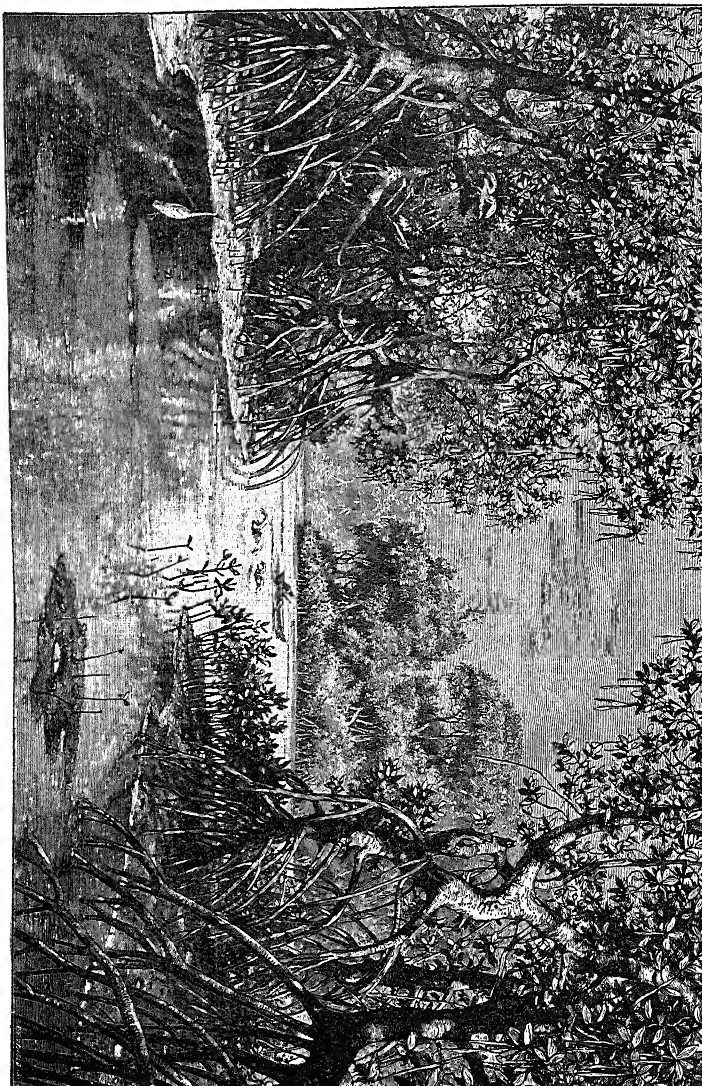


FIG. 284.—Mangrove forest in Lower India. (From Ratzel, *Die Erde*.)

feet above it, with peat ten feet thick filled with cypress stumps, and Dismal Swamp in Virginia and North Carolina, with an area of 500 square miles, near the sea and only a few feet above it and with a peat deposit at least fifteen feet deep (Fig. 281). In this swamp, the chief plants are canes, wild grape, the bald cypress (Fig. 282) and junipers, with but little sphagnum. Similar swamps occur in Florida (Fig. 283), and extensive cedar swamps with peat up to fifteen feet in thickness exist on the Atlantic coastal plain

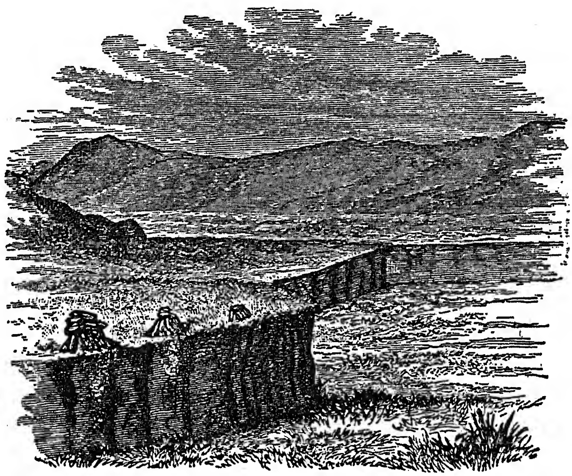


Fig. 285. — Section of a Scottish peat-bog. The peat is underlain by clay, which corresponds to the under-clay of a coal seam. (After Geikie.)

further north. This peat is full of tree trunks and is very pure, containing only 3.35 per cent of ash. In tropical swamps the peat-moss, Sphagnum, is absent, the peat-forming plants being sedges, grasses, myrtle, etc., and woody plants, as in Bermuda, where the peat is at least 50 feet thick in one swamp, and in the Amazon region, and in the interior of Africa. Woody plants are the chief peat-formers in the great tropical swamp of Sumatra, where the peat has been sounded to a depth of nine meters. Here herbaceous plants are rare, and sedges, grasses, and mosses are practically wanting. Thread-like algæ are, however, numerous in the water. Where swamps occur along tropical seacoasts, mangrove trees form the chief vegetation (Fig. 284).

Bogs. — These form on uplands, often directly over rocky or sandy bottoms, where no standing water exists, the water for the

formation of the peat accumulating as the growing vegetation arrests the drainage. Thus actual ponds or lakes may be formed on gentle hillsides or near their tops, the water being held entirely by dams of vegetable material. Such bogs cover the uplands of many northern countries, as for example Great Britain and Ireland, Scandinavia, parts of Canada, etc., being most common in cool and moist regions (Fig. 285).

In the formation of these bogs the peat moss *Sphagnum* is most active, this plant growing rapidly upon moist surfaces and building up a spongy mass which collects and holds back the water. In the Scottish and other uplands, heather is an important peat-maker, for it too holds back the moisture and builds up spongy masses from its decaying older branches and roots (Fig. 301 *b*, p. 364). The common reed (*Phragmites*, Fig. 279) is another important peat-former in the uplands, and so is the bulrush (*Scirpus*, Fig. 278 a_2), the cotton grass (*Eriophorum*, Fig. 278 *c*), and others. In the Arctic Tundras, which are great peat-deposits covering the frozen ground, mosses and lichens are important peat-formers.

Fig. 286. — Gathering peat in an Irish peat-bog.

The peat formed in bogs is known in Great Britain as *hill peat* and is extensively used for fuel, being cut into cubes, which are dried in the open (Fig. 286). It is usually a brownish or nearly black, fibrous, spongy substance, with the vegetable structure still clearly visible. Tree stumps are common in it, as are also fallen trunks and branches, for whenever the peat begins to grow in forested areas, the elevation of the water-level around the trunks, due to the retention by the peat, causes the death of the trees. The generally monotonous deforested areas of these uplands are the result of such a process. In thickness, these upland peat deposits seldom exceed 50 feet, and usually they are much thinner.

Altered Deposits of Older Vegetal Material

Brown-Coal. — This is a compact or earthy coal, of more or less homogeneous character, and pale yellow to deep brown color, burning with a sooty flame and strong odor. It is an altered peat deposit, often still showing evidence of organic origin, and contains from 55 to 75 per cent of carbon. Its specific gravity ranges from 0.5 to 1.5. Brown-coal is most common in the Tertiary formations, and often reaches a great thickness, this, in some of the north German deposits (Fig. 287), being from 75 to 150 feet, while in Australia beds of brown-coal of much greater thickness are known. Old tree stumps in the position of growth are commonly found in these deposits, as shown in the illustration (Fig. 287).

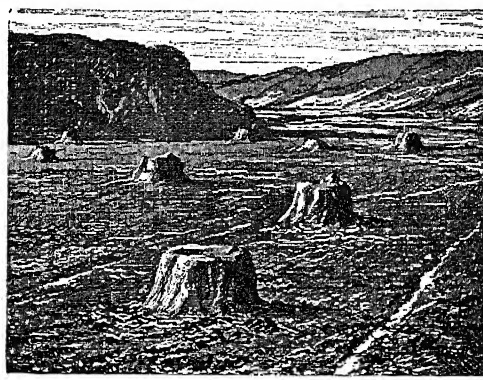


Fig. 287. — Brown-coal quarry near Senftenberg, North Germany. Many stumps of large trees are still standing in the position of growth. (After E. Haase, from Walther.)

Lignite. — This name should be restricted to altered woody tissue such as is found embedded in brown-coal, though in some cases the bulk of the deposit may be of this origin. In general, the woody structure is still recognizable in lignite. The lignites which occur embedded in the north German brown-coal deposit still retain the form of the fallen tree trunks and standing stumps (Fig. 287), and they are found to be of the same types as those still growing in our Dismal and other modern swamps, but which have become wholly extinct in northern Europe. Lignites are also found embedded in sands and clays of Tertiary and Mesozoic age in many regions.

Bituminous Coal. — This is the common soft coal, of black color, bright luster, and usually very brittle character. It contains from 75 to 90 per cent of carbon, and generally some sulphur. Its specific gravity ranges from 1.2 to 1.35, and it burns with a bright, clear flame, though some varieties cake, while others are entirely

consumed to ashes. Under the microscope, traces of organic origin are recognizable, and impressions of plants are commonly found in the shales overlying these coals (Fig. 288). Most of the younger coals (Mesozoic) are of this character, as is also a large proportion of the older coals (Pennsylvanian) of both America and Europe.

FIG. 288. — Fragment of roof shale of an upper Palæozoic coal seam, showing the impression of a fern. About one third natural size. (B. Hubbard, photo.)

Anthracite Coal. — This is hard coal, and is the purest of all, containing over 90 per cent of carbon. It is of black color, submetallic to vitreous luster, and breaks with a conchoidal fracture. Its specific gravity ranges from 1.35 to 1.7. It kindles with difficulty, but burns in a strong draught with great heat without smoke, caking, or odor. Many anthracites are found where the rocks have suffered disturbance, and they may often be regarded as somewhat metamorphosed bituminous coals. Other anthracites, however, are of primary origin, the vegetable accumulations having lost most of their volatile material before burial.

Graphite; Diamond. — Graphite is pure carbon, soft, black, and with the characteristics of a good lubricant. It occurs chiefly in the ancient rocks which have been subjected to metamorphism and changed from bituminous shales, sandstones, and limestones, to graphite-bearing mica schist, gneisses, and marbles. Some graphite may be due to purely inorganic chemical processes. Diamond is crystallized carbon, noted for its hardness and brilliancy of luster.

Natural Coke. — This is another alteration product resulting from contact metamorphism of a coal bed through the heat of an intruded dike or sill. It may also be formed by burning of underground coal beds.

Occurrence and General Character of Coal Deposits

There were three periods in the earth's history when the conditions for the accumulation of extensive deposits of vegetable material were especially favorable, and these deposits have since been converted into brown-coal, bituminous coal, or into anthracite. By far the most extensive accumulations occurred toward the close of the Palæozoic era, when all of the important coals of eastern

North America (east of the 100th meridian) as well as most of those of Europe, and of China, were formed. It has been estimated that seven tenths of the coal deposits of the world belong to this period. The second period was the Cretaceous, in which the Rocky Mountain coals were formed; while the third period, the Tertiary, witnessed the formation of the least valuable of our coals, which occur chiefly west of the 120th meridian, and also that of the extensive brown-coal deposits of North Europe. Some coal is also found in the Triassic of eastern North America, and in small amounts in other horizons in various parts of the earth.

In general, much of the coal was formed from vegetation which grew and was buried where the coal is now found (autochthonous deposits), but some of it appears to have been transported vegetation stranded in favorable localities (allochthonous deposits). Most coals appear to have originated from vegetation which grew in swamps, on broad river flood plains, or on coastal plain areas, and most of them were formed in fresh water. Beds of rock carrying marine fossils are as a rule not directly associated with the coal beds, though such may lie between successive seams. Coals vary greatly in the amount of mineral matter or ash which they contain. Good coals have only from 1 to 5 per cent of ash. When the coal contains 30 or 40 per cent of ash it is called *bony coal* and is valueless. Above that amount it becomes a coal shale.

A typical coal seam (Fig. 289) rests upon a bed of *under-clay* from which much or all of the alkaline material has been removed by the growth of the plants and by solution. This clay is therefore suitable for the formation of "fire bricks" for lining blast furnaces, etc., and the name *fire clay* is applied to it. Such clays are, however, not always present, and they may occur where no coal seam overlies them. The seam itself may vary in thickness from a mere film to many feet (Fig. 290), but the continuity of the thicker seams is generally interrupted by coal shale or layers of bony coal. Overlying it is the *roof shale*, which is consolidated mud, and generally

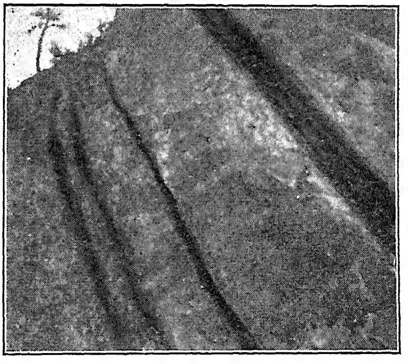


FIG. 289. — Typical coal beds or seams in country rock all steeply inclined by subsequent deformation; California.

contains the well-preserved impressions of the types of plants which grew in the coal swamps. In the majority of cases the rocks between the coal seams are sandstones and shales, but limestone may also occur.

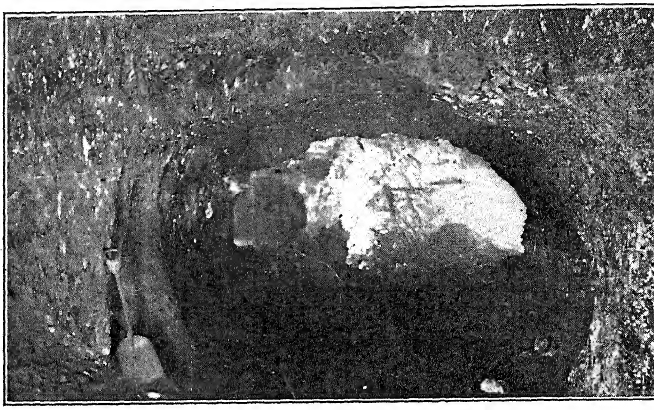


FIG. 290. — Coal-mine in a mammoth vein or bed.

ACCUMULATION OF DECAYING ORGANIC MATTER FROM ANIMAL TISSUES, AND FROM NON-VASCULAR PLANTS

As we have previously seen, there is in every pond or lake a region where only the soft tissues of algæ will grow, and where by their accumulation a layer of much decomposed, structureless material, more or less mingled with mechanical sediment, with lime precipitated by some of these algæ (*Chara*), or with the silicious frustules of diatoms, is formed, to which the name *sapropelite* has been applied (Fig. 291). In deposits of this kind the pollen grains of coniferous trees and other plants growing on the border of the swamp usually abound, and spores of the lower (non-flowering) plants of the neighborhood are also common, and may sometimes predominate. In the stagnant portions of the sea-coast, such as the channels behind the dead coral reefs (Keys) of Florida, previously described, and others like them, there is mingled much decaying animal matter with the decaying plant tissues, and the muds are saturated with the product of this decay. It should be clearly understood that such accumulation cannot, as a rule, take place in unenclosed portions of the sea, for the agitation of the waters there will hasten the dissipation of the products of decay,

and the universally present bottom animals (worms, mollusks, crustaceans, echinoderms, etc.) will devour the organic material, many of them passing the sand and mud through their bodies and extracting its organic contents in the process.

When, however, bottom feeders are scarce or absent, such organic material will accumulate either in pure form, or become

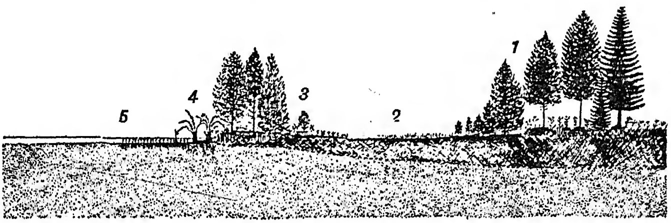


FIG. 291.— Ideal section, showing the approximate relation (1) of the different types of peat, and (2) the plant societies of Algal Lake, northern Michigan. (After C. A. Davis.) The succession of plant associations from without inward is: (1) Tamarack-spruce-cedar swamp, with young tamarack at the inner border; (2) open sedge marsh, with islands of tamarack wood; (3) swamp loose-strife (*Decodon verticillatum*) gradually advancing lakeward, and forming "stools" on which grow mosses, ferns, sedges, and shrubs, finally killing the loose-strife; (4) cat-tail flags; (5) *Potamogeton.* The peat formed by these plants thickens away from the lake, and is humus peat. Below this and forming the lake bottom is a mass of sapropelitic peat, composed of green algæ, with diatoms, and an abundance of pollen-grains of conifers, forming a structureless mass.

mingled with muds and other sediments. The purest material is chiefly confined to lake bottoms, where it is largely composed of algæ mingled with pollen and spores. In the sea the material is practically always mingled with foreign matter and so in decay forms various grades of sapropelites. The principal regions for the accumulation of such matter are the following:

Fresh-water Lakes. — In these accumulations are chiefly vegetable material (algæ, etc.), though some animal matter may also be included. This material may be very pure, forming on decay a *sapropel* (Fig. 291).

Channels and Narrow Lagoons between the Land and Fringing Coral Reefs. —The material accumulating in these is both vegetable and animal. The plants are partly algæ, but the remains of other plants are also included. The animal tissues are those of worms, mollusks, and many other types. There is always a large amount of mechanical sediment in the form of mud, and the product is black bituminous mud-rock or shale (sapropelite), which rests upon the previously deposited limestones derived from the coral reefs, etc.

Mud-flats Formed in the Process of Filling Lagoons. —As we have seen, there is a stage in the formation of marine marshes behind barrier beaches when the eel-grass stage is succeeded by a mud-flat stage, rich in decaying

organic matter, which, with the exception of the eel-grass, is largely of animal origin. Such mud-flats will also form a black bituminous mud-rock, which underlies the coal bed formed by the salt peat if the process of transformation is complete.

Mud-flats of Estuaries and of River Deltas. — In the estuaries of streams, *i.e.* the broad stream mouths where the river water mingles with the encroaching tide, much fine mud is precipitated, and many sea animals, killed by the fresh water, or river animals, killed by the sea-water, will be embedded in this mud and the decay of their tissues will form sapropelitic material. Such muds are formed on the floor of the Hudson River at New York and in many other estuaries. Sometimes vast numbers of river fish are killed by the advancing sea-water, and these form extensive fish beds, the muds being saturated by the decaying organic matter of these fish. Again, vast masses of floating sea animals, such as Foraminifera, pteropods, etc., may be carried into the estuary and killed by the fresh water, and their remains sink to the bottom, where the decaying organic matter will saturate the bottom sediments. On the mud deltas of great rivers, such as the Mississippi, the Nile, etc., much organic matter, both vegetal and animal, will be buried, part of this coming from the river and part being cast upon the delta from the sea during storms and high water. Chief among this material will be the seaweeds and the animals which live attached to them. In this manner the mud becomes saturated with decaying organic matter, which will be a mixture of coal-producing higher plants and organic slime-producing algæ and animal tissues. The mud of the Nile delta contains only from 5.5 to nearly 8 per cent of organic matter, but that of the Vistula carries as much as 23.3 per cent. This river forms a deposit of black mud, locally called pitch, in the Bay of Danzig. On the Mississippi delta many mud lumps or mud craters are formed, from which large volumes of gas, the product of the decay of the organic matter, escape (see Fig. 126, p. 182).

Enclosed Stagnant Seas. — The Black Sea is an excellent example of a water body which, while still maintaining connection with the sea (Mediterranean), is so nearly isolated that its waters are practically stagnant, especially in the lower part. It has been estimated that it takes 1700 years to renew completely the lower waters of this deep basin through the shallow inlets and intermediate salt seas that connect it with the Mediterranean. The upper layers (125 fathoms) are kept fresher by the inflowing drainage from the land, and here many marine organisms live and die. The young of these float in the surface waters, and there are besides many other surface-living animals (plankton) and all of these sooner or later sink to the bottom. There is thus a perpetual rain of organisms descending through the waters of the Black Sea, and these remains accumulate upon the bottom where, because of the stagnant water and lack of oxygen, there are no bottom feeders, only bacteria. These decompose the dead animal matter, and the bottom mud thus becomes richly saturated with these products of decay, in other words, it becomes a rich *sapropelite* in which, moreover, much sulphur, usually in combination with iron, occurs.

Highly Saline Lagoons. — As we have seen, the waters of lagoons separated by a bar from the supplying salt water body, in regions of much evaporation, become intensely saline. The currents flowing into such lagoons

carry large numbers of animals from the main water body, and these are quickly killed by the brine of the lagoon. In the case of the Kara Bugas Gulf, described in Chapter XI, untold numbers of fish and floating Foraminifera, etc., are carried into the brine from the Caspian Sea. As there are no scavengers, *i.e.* animals devouring dead organic matter, in these brines as is the case in normal sea-water, the organic matter accumulates and is embedded with the other deposits of the lagoon. This is a prolific source of organic-decay slime and rich deposits of sapropelite are formed.

Alteration Products from Organic Slime Produced by Non-vascular Plants and by Animal Tissues

According to the degree of admixture of mud and other foreign material with the decaying organic matter from non-vascular plants (algæ) and from animal tissues, we have a series of deposits which ranges from nearly or quite pure organic slime (sapropel) on the one hand, to mud deposits, impregnated to a greater or less degree with this slime, on the other. This last type we have learned to call sapropelite, and it is by far the most common. Pure deposits of the slime, however, also occur and are known from their alteration products, of which *cannel coal* forms the most important. The sapropelites are generally known as bituminous muds or as bituminous shales when consolidated. The organic matter contained in them is, however, often concentrated elsewhere in the form of petroleum and various other hydrocarbons (asphalts) and may separate out as natural gas, etc. We will briefly enumerate the chief characteristics of each of the important types.

Cannel Coal. — This is generally held to be formed from the fresh-water algæ which accumulate in the deeper portions of ponds and swamps, and also often to a large extent from spores, and from the pollen grains of higher plants, blown into these water bodies. Cannel coal has a compact amorphous structure and a dull luster, and commonly a greasy or silky appearance on the fresh surface, a character quite distinct from that of coals formed from the higher plants. This is often well brought out where layers of cannel coal alternate with layers of ordinary bituminous coal, or where the roots of higher plants were embedded in the slime which formed the cannel coal. Such layers of bituminous coal, or such roots of higher plants, when changed to coal, will always have a bright luster in marked contrast with the dull luster of the cannel coal. That animal tissues also add to the slime from which cannel coal is produced is shown by the remains of their hard parts (bones, etc.) in the coal. Thus the cannel coal of Linton, Ohio, has furnished the skeletons of more than fifty species of fishes and amphibians, many of them represented by numerous individuals. Other names given to cannel coal are *boghead* and

torbanite (Scotland). According to some authorities, the waxy and resinous spores of higher plants are more important in the formation of cannel coal and fresh-water sapropelites than are the algæ. They are certainly better preserved than the algæ, and their apparent importance may be more largely due to this fact.

Jet. — This is a deep black, brittle, solid bitumen, segregated in more or less lens-shaped masses in rocks formed of muds which were saturated with organic slime (sapropelites). It appears to be a concentration product of this

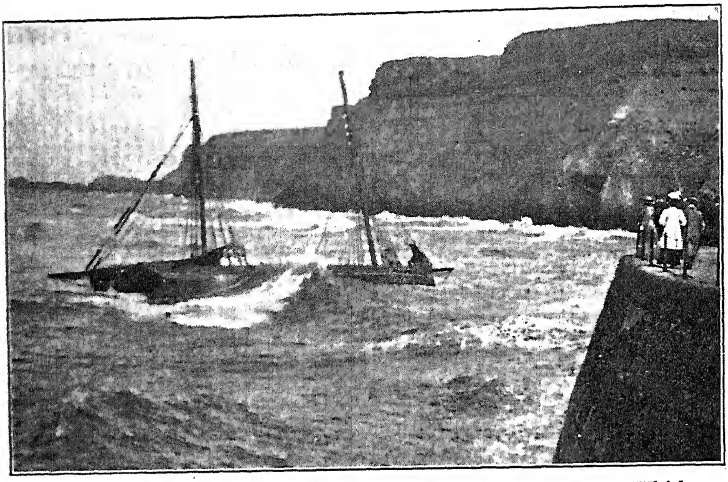


Fig. 292. — Cliff of Jurassic (Liassic) sandstones and shales at Whitby on the North Sea coast of England. In these strata the famous Whitby jet is found.

organic matter and is often found to saturate or replace pieces of fossil wood embedded in the muds or is associated with fish scales and the remains of other organisms. Jet is characterized by its hardness (which is greater than that of asphalt), its conchoidal fracture, and by being less brittle than coal. It is susceptible of a high polish and is much used for ornamental purposes. Important jet-producing rocks are the shales of Whitby, England (Fig. 292), the oily slates of Württemberg, and the similar shales of ancient Lycia in Asia Minor, where the exposure on the Gagas River forms the original locality from which this mineral (often called gagatite or gagates) was obtained. An analysis of jet from Württemberg gave the following result.

Carbon (C), 71.0%	Nitrogen (N), trace
Hydrogen (H), 7.7%	Sulphur (S), trace
Oxygen (O), 23.3%	Ash, 0.9–2.9%

Asphaltum and Special Varieties of Solid Hydrocarbons. — There is a considerable number of solid hydrocarbons found in various parts of the world, and these are probably, for the most part, the products of alteration of organic matter of the non-vascular plants or of animal tissues and therefore members

of the sapropel series. A volcanic or other origin, however, has also been suggested for some of them. They are generally black and brittle, and distinguished from coals by their fusibility. The general name *asphaltum* or bitumen is given to these, and their distribution is world-wide. To the pasty, viscid varieties the general name *maltha* is applied. When sandstones or other rocks are saturated with asphalt, the mixture is called *asphalt rock.* What is probably the most remarkable occurrence of asphalt is found on the island of Trinidad off the northeast coast of South America, where, in what is regarded as the crater of an old mud volcano or geyser, occurs the famous "*Pitch Lake*" of Trinidad, the material of which is an emulsion of water, gas, bitumen, and some other organic substances and mineral matter. The water is saline and contains also borates and ammoniacal salts; the gas is principally hydrogen sulphide and carbon dioxide. The bitumen is high in sulphur, the composition when purified being,

Carbon (C), 82.33%	Sulphur (S), 6.16%
Hydrogen (H), 10.69%	Nitrogen (N), 0.81%

In other hard asphalts the sulphur has been found to range from 3.28 to 9.76 per cent, and in soft asphalts or *malthas* from 0.6 to 2.29 per cent.

Some of the more important varieties of solid bitumen are (*a*) *Ozokerite*, occurring in the Tertiary rocks of the Caucasus, the Carpathians, and in Utah,

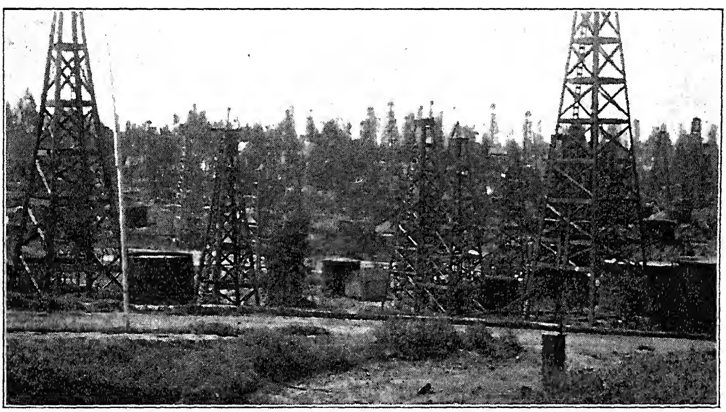


FIG. 293. — A typical view of an oil field, showing derricks and storage tanks.

and forming an important source of paraffin; (*b*) *Albertite* and (*c*) *Grahamite*, similar hydrocarbons occurring in vein-like fissures in the country rock in New Brunswick and West Virginia, respectively, having probably been injected when in a fluid state. (*d*) *Uintaite* or *Gilsonite*, also a black, brittle and lustrous mixture of hydrocarbons found in the Uinta Mountains of Utah and in many other localities..

Petroleum (Fig. 293).—This takes first rank among the products of decay or distillation of the organic slime, but may also be formed by the distillation of the coaly deposits from vascular plants. Nevertheless, the organic matter of sapropelites (the sapropel) *i.e.* algæ and spores among plants, and animal tissues

probably forms the chief source of petroleum. Different petroleum deposits have a different origin, and those of the several geological horizons will be referred to again in their proper place in the section of this book dealing with Historical Geology. The oldest (Palæozoic) petroleum deposits of North America probably were derived from bituminous shales formed either in mud-flats or in delta deposits (Trenton-Utica oils), in lagoonal deposits, behind coral reefs (Onondaga-Marcellus oils), or in estuaries (later Devonian and younger Palæozoic oils), though an origin in enclosed basins of the Black Sea type has also been suggested for some of these. Although the source of the oil is the bituminous mud-rock, the accumulation takes place in more porous limestones or sandstones (oil sands) which are associated with them, and abounds only where special structures (anticlines, domes, etc.) furnish the proper conditions. In the following diagrams (Fig. 294) the relationship of the bituminous shales (the oil producers) and the limestones or sandstones (the oil storers) is shown.

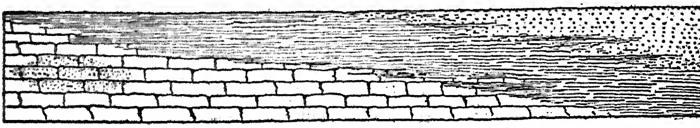


FIG. 294. — Diagram showing the relationship of the black sapropelitic shales, the oil producers (fine lines), to the limestone beds on the left and the sands on the right. If the former contain porous members, or areas of dolomitization (dotted and blocked) these will form oil pools, the oil passing laterally into the reservoir rock. The sandstones on the right will also receive oil from the shales, but unless there is a capping-rock, this oil will become dissipated.

As will be noted, the oil will have to pass laterally into the more porous rock which replaces the bituminous mud-rock, from the organic matter of which the oil is formed.

Many if not most of the petroleum deposits in the younger (especially Tertiary) rocks of America and Europe appear to be derived from the alteration of the organic material of algæ, especially diatoms, and the flesh of animals, ranging from protozoans to fish or even higher types. In nearly all of the great deposits, these organisms appear to have been carried into enclosed bodies of water such as the Black Sea or the Kara Bugas Gulf, where, owing either to the stagnant character of the water or to its high salinity, they perished, their organic tissues accumulating in the sediments because of the absence in these waters of scavengers or animals feeding upon such matter. Thus the California oils are believed to have been derived from the soft tissues of marine diatoms which accumulated in vast quantities under special conditions which insured the non-consumption or incomplete dissipation of the decaying organic matter. Fresh-water diatoms accumulating in lakes also have furnished such materials. The oil of the Caucasus and perhaps of some of the Carpathian regions may be largely derived from the organic matter of fish killed in large quantities in the stagnant or highly saline waters of embayments or basins of the Black Sea type, as were the oil and asphalt of the Alsace-Lorraine region and that forming to-day in the vicinity of the Kara Bugas Gulf, where vast numbers of fish are constantly killed, as already described.

Finally, some of the oil of the Carpathian region may have originated from the Foraminifera and other floating (planktonic) organisms carried into similar lagoons, in some of which salts were being deposited.

It must also be mentioned that petroleum has been held to be, in some cases at least, of inorganic origin, formed by descending waters which came in contact with heated metallic carbides in the interior of the earth's crust, the reaction there resulting in the formation of metallic oxides and the liberation of hydrocarbon and of carbon dioxide as the final product. This theory, proposed by the Russian chemist, Mendelieff, is, however, very generally discarded in favor of the theory of organic origin, which is fully supported by the facts known in the cases of most large petroleum deposits.

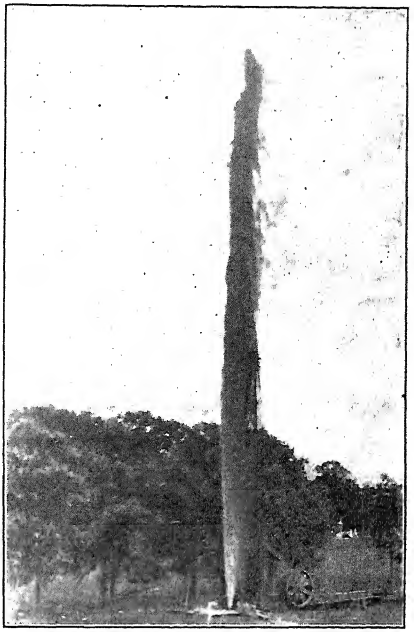


FIG. 295. — A gushing oil-well.

Natural Gas. — This is essentially similar in origin to petroleum, representing the volatile hydrocarbons. It is commonly associated with petroleum, but may also occur where this is not found.

Bituminous Shales, Oil Shales. — These represent the solidified muds of lagoons, stagnant basins, mud-flats, etc., which are impregnated with finely disseminated organic matter. Although the names are used somewhat loosely, the term *bituminous shale* is best applied to those carrying finely divided, partly decomposed remains of vascular plants, while the *oil shales* are saturated with the product of decay of non-vascular plant and animal tissues, *i.e.* the true sapropel, and these form the true sapropelites. Bituminous shales thus pass into coal deposits, but petroleum may also be derived from them. The sapropelites, however, appear to form the true and important oil shales.

CHAPTER XIV

ATMOSPHERIC PRECIPITATES AND THEIR DERIVATIVES

Types of Atmospheric Precipitates

The atmospheric precipitates include rain, hail, and snow; their derivatives are ice and the special form of the latter — the glaciers. There are other atmospheric precipitates, such as nitrogen compounds formed by electrical discharges, etc., but these need not be considered here, though they may at times become of importance.

Materials in the Atmosphere

As has been stated in an earlier chapter, the atmosphere is a mixture of oxygen and nitrogen and contains, besides minute quantities of other substances, a fairly definite amount of carbon dioxide (CO_2) and a variable quantity of water vapor (H_2O). The carbon dioxide is taken from the atmosphere by the higher plants, which, by means of the leaf-green (chlorophyll) in their cells, can, under the influence of the sunlight, decompose the carbon dioxide, so that the carbon can be utilized to build up the tissues of the plant while the oxygen is given off again through the breathing pores. Carbon dioxide also combines with certain minerals in the rocks of the earth, but no direct precipitation of this substance takes place, nor are any notable compounds formed in the air that are precipitated.

If we omit the precipitates formed by gaseous emanations from volcanoes, the only important substance which returns to the surface of the earth from the atmosphere is the water held there as invisible vapor and the various forms which this compound assumes.

The Water of the Atmosphere

Sources of Water Vapor. — The great source whence the moisture of the air is derived is the sea, and the process of translation of this water into vapor form is *evaporation*. Evaporation, however,

takes place all over the lands as well, where not only lakes and rivers, but also the moisture of the soil is drawn upon to supply the air with water vapor. Vegetation takes the moisture from the ground, and this, circulating through the plants, is in part evaporated from the leaves, sometimes at such a rate that the plant droops.

Absolute Humidity of the Air. — The total amount of water vapor in the air marks its absolute humidity. This, however, signifies little, for the same amount of vapor in the air at high temperature will leave that air very dry, while at low temperature it will be moist.

Saturation of the Air. — When the maximum amount of water which the air can hold at any given temperature is reached, the air is said to be saturated. A cubic foot of air can hold half a grain of water at 0° F., at 60° it can hold 5 grains, and at 80° it can hold 11 grains. The air of a room 40 by 40 by 15 feet in dimensions can hold nearly 20 pounds of water when the temperature is 60° F., or nearly enough to fill a common water pail. At 80° F. it can hold more than twice that amount. When the saturation point of the air is reached, the slightest fall in temperature will cause precipitation. This critical point is called the *dew point.*

Relative Humidity. — Ordinarily the air holds less water than it is capable of holding at that temperature. The ratio in per cent between the quantity of water which the air actually contains and the maximum amount which it could contain at that temperature marks its relative humidity. Thus in the case of the room cited above, if the amount of water which the air can contain is 20 pounds, but the amount which it actually contains is only 10 pounds, the relative humidity is 50 per cent. At saturation (20 pounds in the example cited) the relative humidity is 100 per cent.

The average relative humidity of the air over the land is about 60 per cent, while over the oceans it is about 85 per cent. It is, of course, not uniform, especially over the land, where great variation exists. When the relative humidity is below 65 per cent, the air is said to be dry, no matter what its temperature. Thus it appears that regions of dry air are far more extensive than those of moist, to make the average humidity 60 per cent, or the excessive dryness of some regions greatly lowers the general average, in spite of the fact that some localities have a very high humidity. In semi-

arid regions the relative humidity ranges around 45 per cent, and in desert regions between 25 and 30 per cent. The lower the relative humidity, the greater is the evaporation from the surface of the earth.

Precipitation of Atmospheric Moisture

When the air is saturated, the slightest drop in temperature will inaugurate precipitation, because with it the capacity of the air for holding water is decreased, and the excess above saturation must be eliminated. If the temperature of the air is above freezing point, this precipitation will take the form of rain; if below, it will be snow or hail. Clouds merely represent the preliminary stage of separation of the water vapor from the atmosphere.

The rain water, in so far as it is not re-evaporated, either runs off as surface water in the form of rivulets which unite to form larger streams (the run-off), or it sinks into the ground to become a part of the subsurface water of the hydrosphere. The snow, however, generally accumulates where it falls, except for modification by the wind (snow drifts) and becomes a permanent cover of unconsolidated material at least for a period of time, if the temperature of the air in contact with it is below the freezing point. If it is above that, snow melts or evaporates, and the water produced by melting becomes a part of the hydrosphere, running off as surface water or sinking in, to become subsurface water. If the air becomes dry, *i.e.* if its relative humidity falls or a dry wind blows across the snow field, direct evaporation of the snow takes place, that is, it will pass from the solid directly to the vapor stage. As a result of such evaporation the surface of the snow is commonly pitted or marked by shallow hollows or concavities.

The Snow-line

The lower limit of the permanent snow fields of the earth constitutes the *snow-line* which, in general, corresponds to the line which connects the points where the mean summer temperature of the air is 0° C. (+32° F.). There are, however, many modifications of this relation, due chiefly to the amount of precipitation during the winter months, the amount of sunlight, the course of drying winds, the steepness of the slope, the altitude, and the protection in ravines and shady valleys. The height of the snow-line above sea-level varies in general with the latitude. In the

Bolivian Andes, near the equator, it is 18,500 feet on the western side and 16,000 feet on the eastern. In Lapland (latitude 70° N.) it lies 3000 feet or more above the sea, and in Greenland (lat. 60°–70° N.) about 2200 feet. In higher latitudes it approaches sea-level.

The lower limit of snow fall, and the snow-line, or lower limit of permanent snow, do not of course, correspond. In latitude 40° N. snow falls at sea-level, but the permanent snow-line is on the average 3000 meters higher. Mountains in this latitude, below that elevation, have permanent snow only in protected ravines. In the tropics the difference in altitude between the lower limit of snow fall and the snow-line is much less.

Compacting and Modification of Snow

Granular Snow. — When precipitated, snow is a loose aggregate of needles and flakes of crystalline form and structure. This crystalline character is, however, soon lost by partial melting and evaporation, and a fine granular powder results, this representing the first stage in alteration.

Firn or Névé. — When the grains of snow become loosely held together, or united by a cement of ice, the *névé* or *firn* is produced. The aggregate thus formed is full of air bubbles, and it represents the second stage in modification (Fig. 304, p. 367).

Snow Ice or Glacier Ice. — In this substance the change has progressed so far that the mass has become a granular crystalline ice in which the individual crystalline ice grains range from the size of a pea near the firn border, to that of a hen's egg in the lower portion. The crystals are intimately united, so that in fresh ice they cannot be distinguished. Ice is formed slowly from snow by a process of compacting which eliminates the air spaces of the firn or névé and brings the crystals in close contact. This may be produced by pressure, by percolating waters which by freezing replace the air cavities, or by the growth of the new crystals themselves from the moisture due to evaporation of the smaller crystals, or that resulting from partial melting.

Glaciers

Glaciers are produced by the spreading or out-flow from the center of accumulation of the ice which has resulted from the compacting of the snow. According to the mode of occurrence

of such spreading ice masses, we may recognize (1) *true glaciers, i.e.* valley or mountain glaciers, (2) *confluent* or *piedmont* glaciers, (3) *ice caps*, and (4) *glacial sheets* or *continental glaciers*.

True Glaciers

True glaciers are confined to more or less definite channels, bounded generally by rock walls and comparable in many respects to streams of water (Fig. 296). Such ice streams may reach a

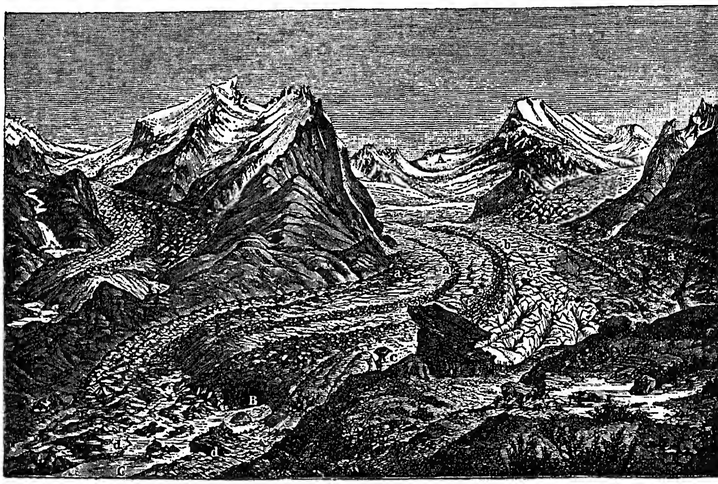


FIG. 296. — Ideal glacier landscape. *A*, firn or névé; *B*, mouth of glacier tunnel; *C*, glacial stream; *a*, lateral moraines; *b*, medial moraine; *c*, glacial table; *d*, terminal moraine. The ridges between the two glaciers are serrated forming *arêtes* or *grats*. (After F. Simony; from Ratzel, *Die Erde*.)

length of fifty miles or more, as in the great Seward glacier of Alaska, the main feeder of the Malaspina glacier (see map, Fig. 320, p. 381) in which the width at the narrowest point is three miles (Fig. 321, p. 382). Most of the alpine glaciers, on the other hand, are not over a mile long, though the largest, the Aletsch Glacier, is more than ten miles in length. The thickness of the alpine glaciers rises in some cases to 800 and in exceptional ones to 1200 feet.

The most typical glaciers are found upon the mountain sides and in well-defined mountain valleys, the best known examples being in the Alps. They are commonly called valley or mountain glaciers, the latter term applying especially to the short glaciers

which lie in the depressions in mountain sides, these depressions being often due to the erosive work of the glaciers themselves. Typical valley glaciers, also called *dendritic glaciers,* because they usually have many branches, most commonly occupy large structural troughs in the mountain regions, especially in high latitudes, though they may also fill old erosion valleys. The course of a typical valley glacier may be straight, but is more often a winding one. It may

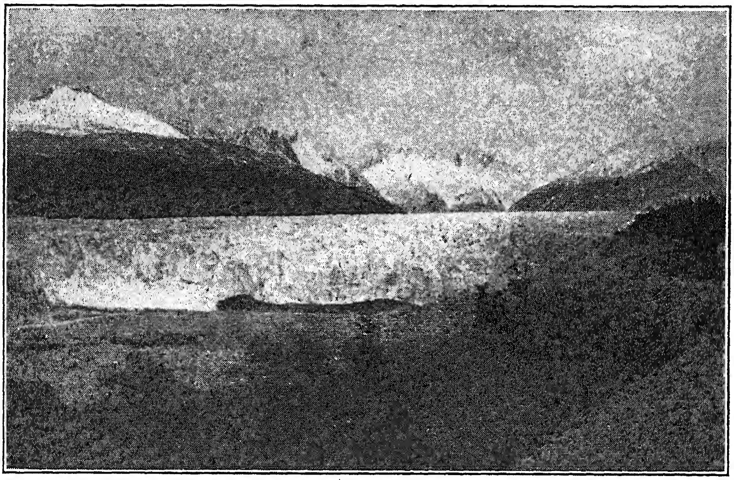


FIG. 297. — Abrupt front of an Alaskan glacier, with a deglaciated valley in front partly occupied by a glacial stream. (Seward division, Gov't R. R.; by courtesy of Alaska Engineering Commission.) Compare Fig. 314, p. 376, abrupt glacier front on coast.

be simple throughout, or two or more streams may unite to form a main trunk, as in the case of the junction of several rivers into a main trunk stream, while, moreover, the main glacier may receive lateral tributaries. According to location, altitude, and other causes, the lower end of the glacier may be more or less abrupt (Fig. 297) or it may spread out upon the flat foreland to form a *fan glacier,* which by the union with similar fans of neighboring ice streams forms a *piedmont glacier.* Examples of the several types will be described in some detail.

The Great Aletsch Glacier of the Alps (Figs. 298, 299). — In the Bernese Alps of central Switzerland, where the Jungfrau, the Aletschhorn, and other great peaks dominate the landscape, we find a great center of modern alpine glaciation. From the southern

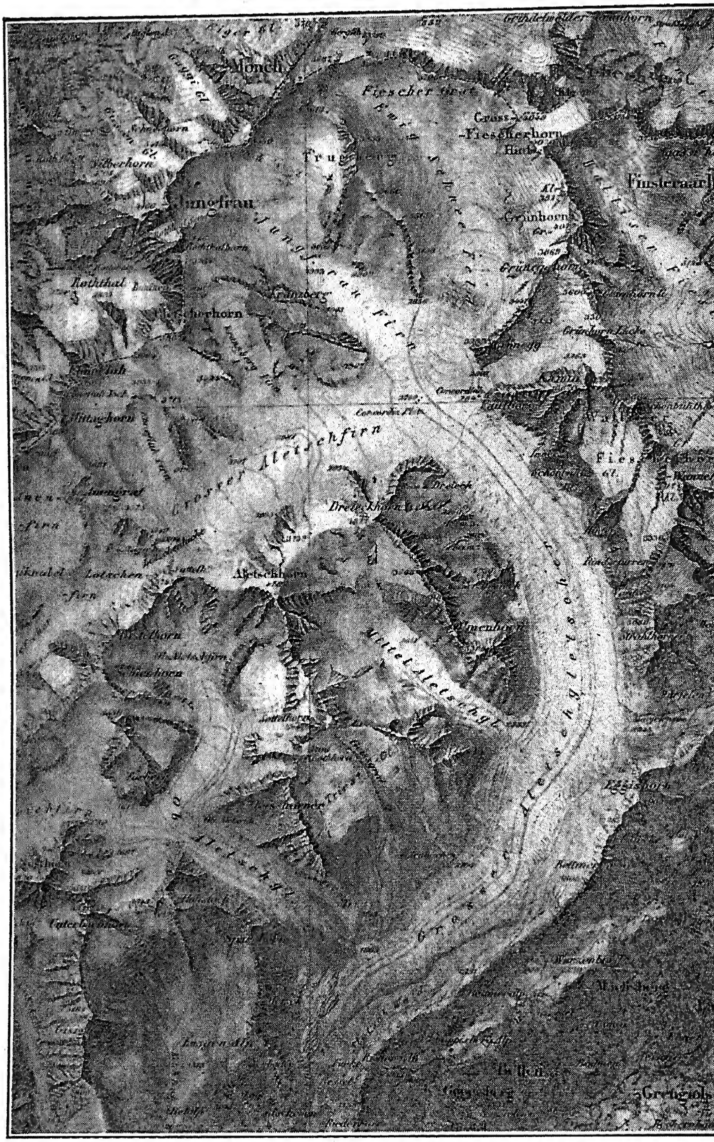


FIG. 298. — Map of the Aletsch Glacier and the surrounding territory in the Bernese Alps of Switzerland. From the Swiss Government map.

and eastern sides of these mountain ranges descends the Great Aletsch Glacier toward the valley of the Rhone, without, however, reaching it. This glacier, which in many respects is the finest in

FIG. 299. — The Aletsch Glacier in Switzerland, showing banding due to medial moraines and a temporary glacial lake (the Märjelen See) formed where the ice dams a small side valley. As seen from the Eggishorn. (Courtesy of Prof. D. W. Johnson.)

the Alps, occupies a mountain valley for about ten miles of its length, and is bordered, for the most part, by high ranges and peaks on either side, the largest of which is the Aletschhorn (4182 meters or

13,768 feet high, 132 feet higher than the Jungfrau) from the base of which tributary glaciers join the main ice stream (Fig. 298).

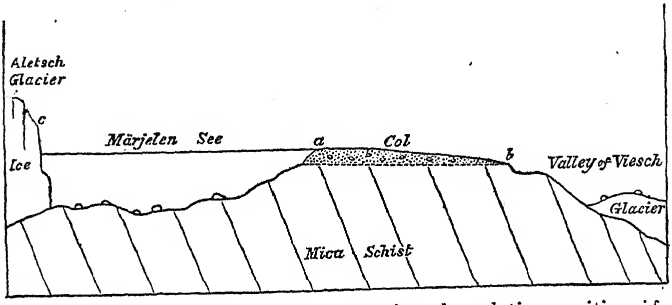


FIG. 300 *a*. — Diagrammatic section, showing the relative position of the Märjelen Lake, the Aletsch Glacier which holds it and the valley of the Viesch into which it drains when full. *a*, *b*, col or dividing ridge between the two valleys; *c*, vertical cliff of ice forming the dam. (After Lyell.)

On its eastern border a tributary valley, partly free from ice, is dammed by the glacier of the main valley, and behind this ice dam lies the famed and beautiful Märjelen Lake, a typical example

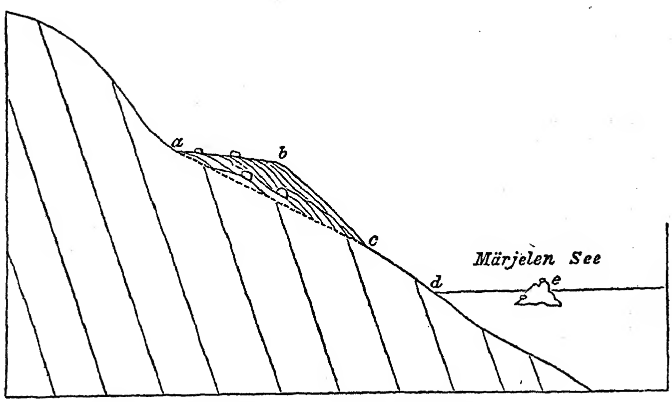


FIG. 300 *b*. — Section of glacier lake called the Märjelen See. *a*, *b*, *c*, terrace of detrital matter formed on the margin of the lake when full; *d*, surface of the lake 40 feet below its usual level; *e*, mass of floating ice with included stones detached from the dam; *f*, boundary hill composed of mica schist. (After Lyell.)

of a lake produced by ice-damming of a valley (Fig. 299). This lake is periodically drained, partly or completely, every three to five years by the opening of some outlet under the ice, with disastrous floods in the valley below. Ordinarily, however, it is held

in by a precipitous wall of ice of the Aletsch glacier. After drainage it fills up in about a year to a level determined not by the height of the glacier dam, which always rises much above the lake, but by the water-shed or col which separates the lake from the valley of the Fiesch (or Viesch) glacier on the east into which it drains when full (Fig. 300 *a*). Around the margin of this lake, terraces or beaches of sand and gravel are built, which are exposed when the lake is drained. A characteristic section of such a beach (Fig. 300 *b*) shows a surface shelf, sloping from 5° to 15° toward the lake, and about 16 paces wide. At the edge of this slope, which marks the level of the lake when full, there is a sharp change, the beds de-

FIG. 301 *a*. — The Parallel Roads of Glen Roy. (W. Lamond Howie.)

scending at an angle of 29°. This is the underwater slope of the deposit, and represents the angle at which the beds (fore-sets) are laid down. The sands are bedded, but contain no organic remains, since the temperature of the water is always near freezing. Over the beach and bottom are scattered many large blocks of stone left by icebergs which break from the main glacier wall.

In one of the glens in the Scottish Highlands, known as Glen Roy, there are several old beach lines at successive levels, along the sides of the glen, which are known under the name of the Parallel Roads of Glen Roy (Fig. 301 *a*, *b*). The natives regard these as roads made by the "gentry" for fishing purposes when the glen was a lake. A study of the glen has shown that it was once blocked by a glacier at the lower end, as is the Märjelen Lake to-day, and that it was filled by a lake, the several levels being due to the

progressive opening of *cols* permitting drainage, at successively lower levels, into other valleys after the manner of the drainage of the Märjelen Lake into the Viesch Valley, the col of which determines the height of the lake and the beaches (Fig. 302).

FIG. 301 *b*.—Photograph of one of the terraces or "parallel roads" in Glen Roy, Scotland, showing the distinct notch which it forms upon the side of the glen, and the dense growth of peat-forming vegetation; largely heather. (Photo by author.)

From the foot of the Aletsch Glacier issues the turbulent Massa River, which joins the Rhone several miles below, and more than doubles the volume of that stream. It has been said that other glaciers send forth torrents from the ice caverns at their foot; this one alone pours out a river. The Rhone carries down to Naters the drainage of its own glaciers supplemented by a dozen other ice-fed streams; yet these combined waters are far exceeded in volume by those brought by the single stream from the Aletsch Glacier. It has been questioned, indeed, whether the united torrents of any four glaciers in the Alps could equal that single stream.

A fine view of the glacier is obtained from the summit of the Eggishorn (Fig. 299), a peak just south of Märjelen Lake and opposite the tributary Aren or Middle Aletsch glacier, which heads in an amphitheater in which lies the middle Aletsch névé, at the eastern foot of the Aletschhorn (see map, Fig. 298). Farther down, on the same side, is the little Trist or Upper Aletsch Glacier or glacieret, which at present does not reach the main ice stream but rests in a valley, the floor of which is high above the surface of the great glacier. This little glacier is therefore called a hanging glacier or glacieret, being hung, as it were, upon the valley side of the great one. In former times this did, however, extend to the main glacier. It heads in the upper Aletsch névé south of the Aletschhorn, and another one, the Beichfirn or névé, is also tributary to it. These névés lie in more or less horseshoe-shaped valleys

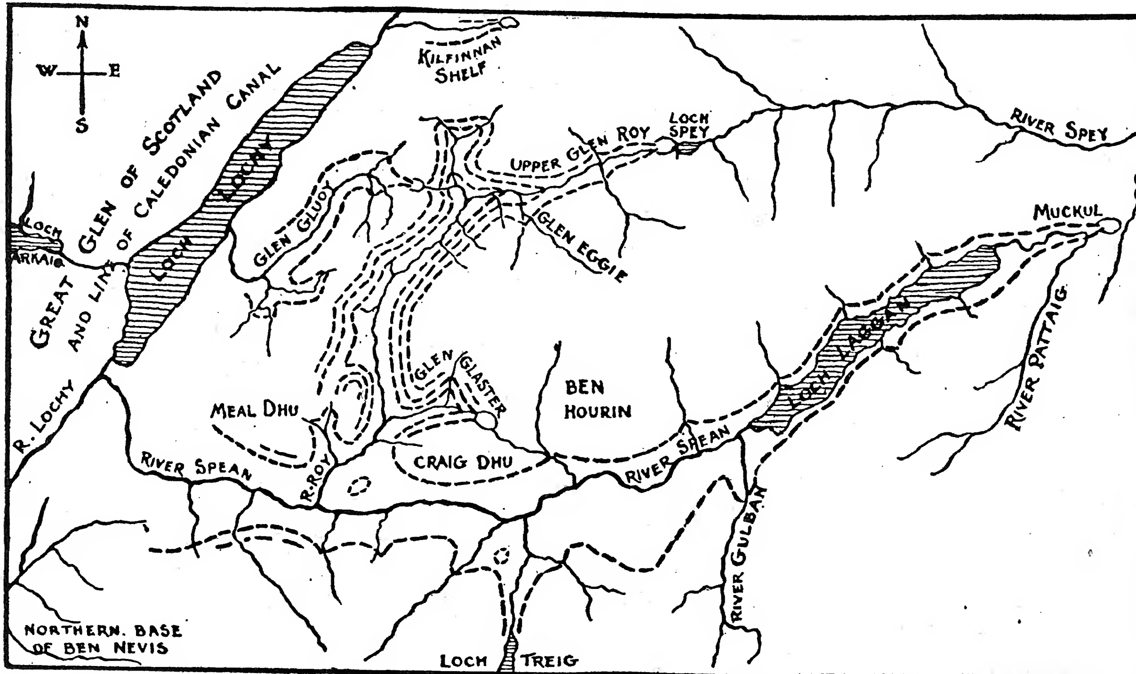


FIG. 302. — Diagrammatic map of the parallel roads of Glen Roy and adjoining glens in Scotland. (After Lake and Rastall.) The dotted lines show the location of the successive beaches, and the outlets into the neighboring valleys are indicated.

or *cirques*, and between them rise the pyramidal peaks of triangular base to which the designation *horn* is applied.

The great Aletsch Glacier itself heads in a group of large névés which extend north of the Dreieckhorn and Aletschhorn and toward the foot of the Jungfrau. On the east lies the Wannehorn, the western face of which is marked by a number of small cirques, the névés of which are tributary to the Great Aletsch Glacier.

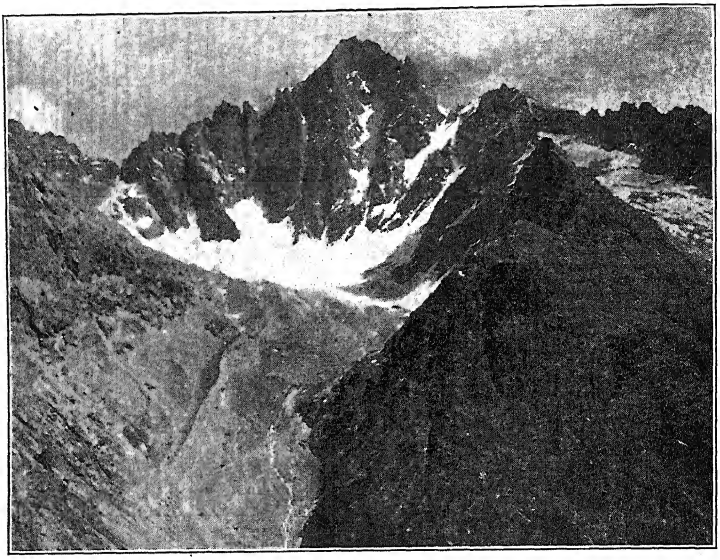


Fig. 303. — Typical glacial cirque with large amount of moraine deposited in foreground. Massif de Pelvoux, Alpes d'Oisaus, France. (Courtesy of Prof. D. W. Johnson.)

These cirques, when well developed (Fig. 303), are semicircular or amphitheater-shaped, with rough, precipitous walls, and comparatively smooth floors filled with névé. Their precipitous walls are due to the plucking and sapping action of the ice which freezes to the blocks and in the cracks at the base of the cliff, and under the influence of partial melting and refreezing pushes away from the wall, carrying the plucked or quarried blocks with it. As the ice moves away from the walls of the cirques a crevasse comes into existence between the rock wall and the ice. This crevasse, called the *bergschrund*, may vary in width from two or three to more than eighty feet, and in depth to 150 feet or more. At the

bottom, much disruption of rock takes place by the freezing of the water which drips into it.

In mountains which were formerly covered by glaciers, such cirques are characteristic features, and their presence, readily

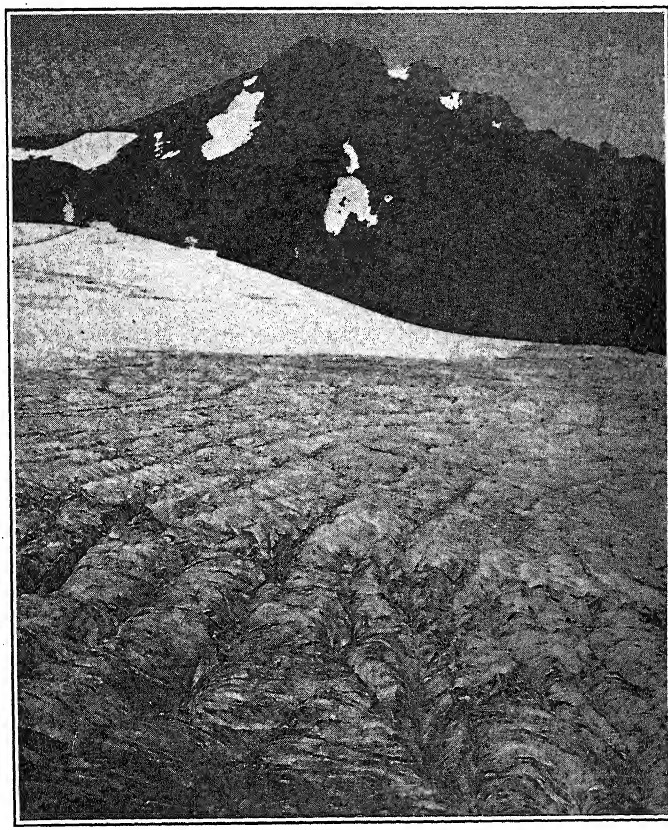


Fig. 304. — Glacier of Three Sister peaks, Oregon, between West and North Sister (the latter shown in the view). — Showing junction of glacier and névé and marginal crevasses. (Photo by I. C. Russell, Aug. 18, 1903, U. S. G. S., by courtesy of *Popular Science Monthly*.)

recognized by their peculiar form, is in itself a proof that such mountains formerly held glaciers, even though these have entirely disappeared. As cirques are progressively cut backwards into the mountains, their walls increase in height, and if cirques approach each other from opposite directions, the space between them is narrowed, and eventually only a sharp, narrow, serrated ridge

remains between them, from which arise the sharp horns (Fig. 296). Later still, parts of the ridge will be lowered to form a connecting col between two cirques (see further, section on glacial erosion in Chapter XXIII).

The névés of the Aletsch really occupy three large and many small cirques or embayments in the mountain complex. On the west between the Dreieckhorn and the Gletscherhorn, lies the great Aletsch névé which also feeds the Lang Glacier descending to the southwest. On the northwest lies the Jungfrau firn or névé, which is bounded by the Gletscherhorn, Jungfrau, and the Mönch on the west and north, and the Trugberg ridge on the east. The Ewigschnee Feld to the east of the Trugberg ridge completes the trinity, while a fourth smaller one north of the Faulberg descends from the Grünhorn Lücke on the east. Crevasses are not uncommon on these névés, but the bergschrund is not everywhere developed. In some cases the névés connect across the cols or passes with others which feed glaciers descending in other directions.

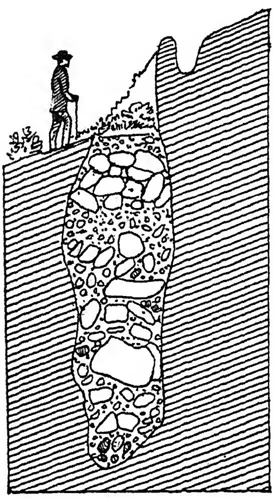


Fig. 305. — Section of an old glacial pot-hole filled with débris, Christiania. (After Brögger.)

The surface of the Aletsch glacier, which is about two miles wide, is often almost free from stones and rock débris except along its sides, where the material falling from the bounding cliffs forms *lateral moraines*. This glacier, unlike most other large glaciers of the Alps, has as a rule no medial moraine or only a feeble one. Along the center, the ice is mostly solid, though narrow fissures or crevasses frequently open in it. Such crevasses are much more pronounced, however, on its eastern margin, which has a convex form (see also Fig. 304). The melting of the ice upon the surface produces pools and streams, which occasionally combine into small rivers. These tumble into the crevasses and produce vertical *chimneys* or *moulins*, which carry the waters to the bottom of the glacier where, by their whirling motion, they often cut "potholes" in the bed of the ice stream. In regions from which glaciers

have departed, such pot-holes are sometimes seen filled with débris (Fig. 305).

The Mer de Glace (Figs. 306, 307). — From the northern slope of the Mont Blanc glacial field on the Franco-Swiss border descends the glacier Mer de Glace toward the Chamonix Valley. At the head of the glacier is a complex of cirques, which radiate outward from the stem glacier to which they are tributary, as the veins of a maple leaf radiate from the petiole. From these cirques, short glaciers or glacierets unite to form the trunk glacier, which flows toward the Chamonix Valley. This is the more common type of glacier found in the Alps, and though the branches are given different names, they are, in a manner, only tributary heads of one principal stream. These smaller glaciers commonly have a much steeper slope than the trunk glacier, and many of them suggest ice cascades, being indeed so named, as for example the Cascade du Talèfre, which joins the Mer de Glace from the east, and the Cascade of the Glacier du Géant on the west (see map, Fig. 306). Such steep glaciers, occupying the depressions in the mountain sides, are more properly termed mountain glaciers, and they are the most common among the 2000 or more glaciers of the Alps, most of which are, however, less than a mile in length.

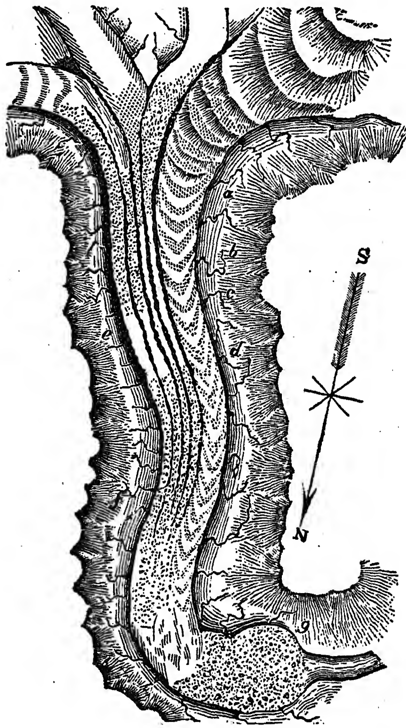


FIG. 306. — Map of the Mer de Glace, French Alps, showing four medial moraines and the terminal glacial stream, the Arveyon. (After Le Conte.) The feeding glaciers are: on the right, Glacier du Géant, with ice cascades and *séracs*, and its tributary, the Glacier des Périades; in the center, the Glacier de Leschaux; and on the left, the Glacier de Talèfre — also showing ice cascades and séracs.

Each of these tributary glaciers has its lateral moraine of rock débris, partly derived from the lateral wall, but also in part brought up from below (see page 493) by movements within the ice. As two streams unite, the lateral moraines on adjoining sides combine to form a *medial moraine*, a more or less continuous line of rock-fragments, sand, etc., which stretches along the central portion of the confluent glacier thus formed. In the Mer de Glace there are several such medial moraines forming parallel lines upon the trunk glacier, which, moreover, has its own lateral moraines.

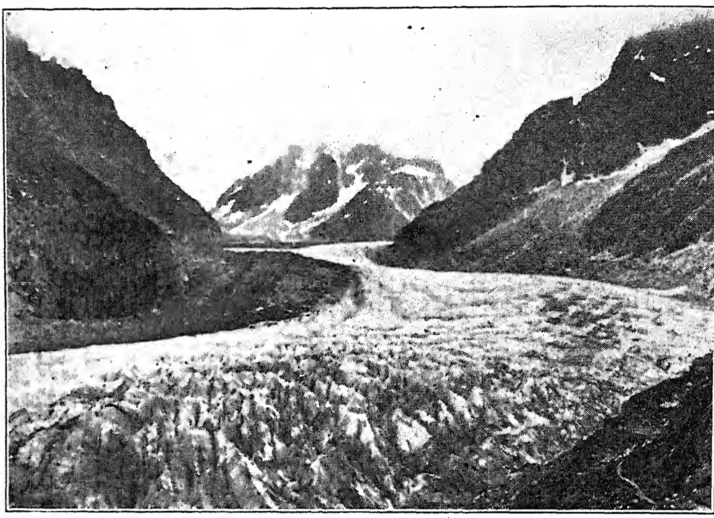


FIG. 307. — The Mer de Glace near Chamonix, French Alps. Note the snubbed lower ends of the mountain ridges indicating the beginning of the U-shaped glacial valley form. (Photo D. W. Johnson.)

At the foot of the glacier where the ice undergoes melting, this material comes to rest to form the *terminal moraine*, which is also built in part of material carried along within or on the bottom of the ice (englacial and subglacial detritus). From the melting of the ice, glacial streams arise, these heading often far back in tunnels under the ice as subglacial streams.

Other Glaciers of Similar Character. — Though the glaciers of the Alps are the most familiar, and in many respects best-studied there are many others in different parts of the world which show the characters so far described on a much larger scale. In the Karakoram Himalayas, several long and narrow valley glaciers are

found, which, moreover, have numerous lateral tributaries similar to streams of water. These form the so-called dendritic or true valley type, of which the Great Aletsch is a small example with few tributaries. Of these larger examples, the Hispar Glacier (Fig. 308) has a length of over 36 miles, and is characterized by numerous tributaries on both sides, which join it approximately at right angles. The main glacier here is very straight. The Baltoro Glacier of the same region and of similar length occupies a curving valley, and its tributaries also join mostly at right angles. They supply

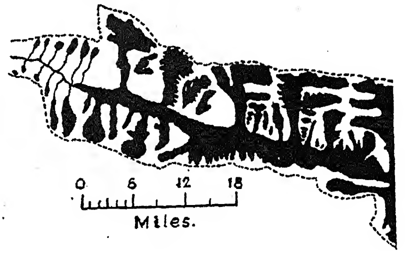


FIG. 308.— Hispar Glacier, a typical valley glacier, with numerous tributaries, Karakoram, Himalayas. (After Martin Conway.) Ice and streams in black drainage territory in dotted line.

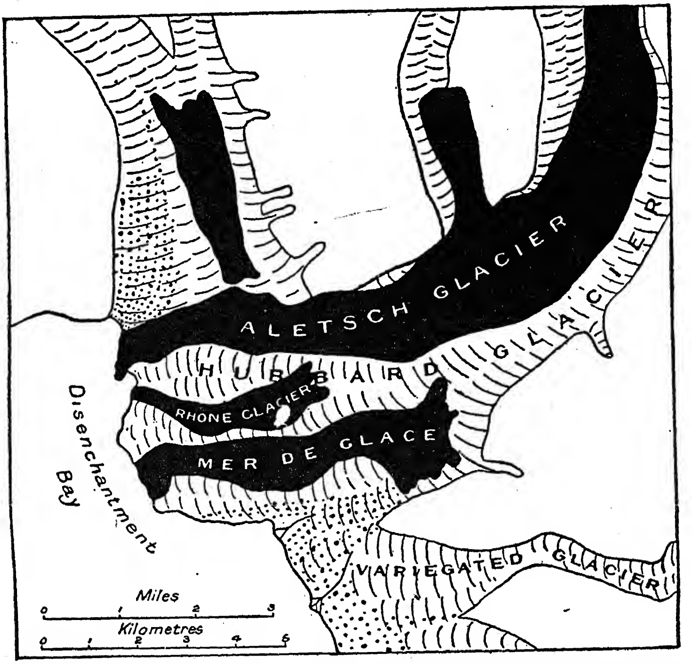


FIG. 309. — Three of the largest ice tongues of the Swiss Alps superposed on the same scale over Hubbard Glacier, Alaska. (Canadian Geol. Survey.)

Fig. 310. — Valley of the Lauterbrunnen, Switzerland. A typical U-shaped glaciated valley. (After de Martonne.)

morainal material from different sources, and as a result this glacier has 15 moraines of different colors. The Tasman Glacier of New Zealand is another example. The Hubbard Glacier of Alaska (location: map, Fig. 320, p. 381) exceeds the combined area of the Aletsch, Rhone, and Mer de Glace, as shown in the diagram on page 371 (Fig. 309).

Characters of the Glacial Valley. — When such glaciers shrink with a change in climate, or disappear entirely, their beds become exposed and show characteristic features. The form of the valley

FIG. 311. — Rounded rock surfaces or *Roches Moutonnées*, due to erosion by a former glacier, Colorado. (After Hayden.)

often resembles in section the letter U, with the sides approximately perpendicular and the bottom rounded (Fig. 310). This is due to the erosive action of the ice and is the characteristic form of a young glaciated valley or one deepened by glacial work. Many ancient valleys in regions now entirely free from ice have this form, and point to former glacial occupancy and erosion or deepening by ice (see also Chapter XXIII).

The eroded bottom of such a valley often shows hummocky surfaces, sloping and smooth on the side from which the glacier moved (stoss-side) and with striated surfaces, but rough and

cliffed on the side away from the movement (lee side). Such rock surfaces when seen from above have a fanciful resemblance to a flock of crouching sheep, on which account the French have called them *roches moutonnées*, a name which has been generally adopted for such erosion surfaces (Fig. 311). They are not confined to glaciated valley floors, but occur in regions of continental glaciation as well.

Where tributary valleys join the main valley they are generally found to do so at a point much above the floor of the latter. The lateral valleys are indeed hanging valleys, there being an abrupt descent from the valley bottoms at their mouths to the bottom of the main trough. This is due to the fact that the main ice stream deepens its valley more readily than the smaller lateral glaciers deepen theirs, and although the surfaces of lateral glaciers ussually accord with that of the main stream to which they are tributary, their bottoms do not correspond (Fig. 312). Along the borders of the great fjords in the "inside passage" to Alaska, there are very many fine examples of such hanging valleys. These fjords themselves represent the old valleys of the main or trunk glaciers, now abandoned by the ice but filled instead by water from the sea. (See further, Chapter XXIII.)

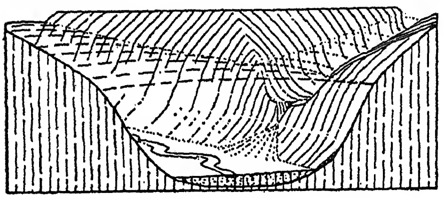


Fig. 312. — Diagram to illustrate the relationship of main and tributary glaciers. The surfaces of the two glaciers are in accord, but the valley of the main glacier is deepened much below that of the tributary glacier. On the melting of the glaciers the valley of the tributary glacier will be a hanging valley, its mouth joining the main valley at some height above its floor. A river flood-plain deposit is formed in the main valley after abandonment by the ice, while an alluvial fan forms at the mouth of the tributary hanging valley. (After Davis.)

Movement of Mountain and Valley Glaciers. — Experiments have been made on the Aar Glacier, in the north of the Bernese Alps, where Agassiz conducted his pioneer studies, on the glaciers at the head of the Rhone valley and on others, to determine the character and rate of movement of valley and mountain glaciers. A line of stakes driven into the ice across the glacier was accurately located by instruments with reference to the rock walls. Measurements of their advance were made at intervals to

determine the rate and mode of progress. A significant fact discovered was that the center of the ice stream moved faster

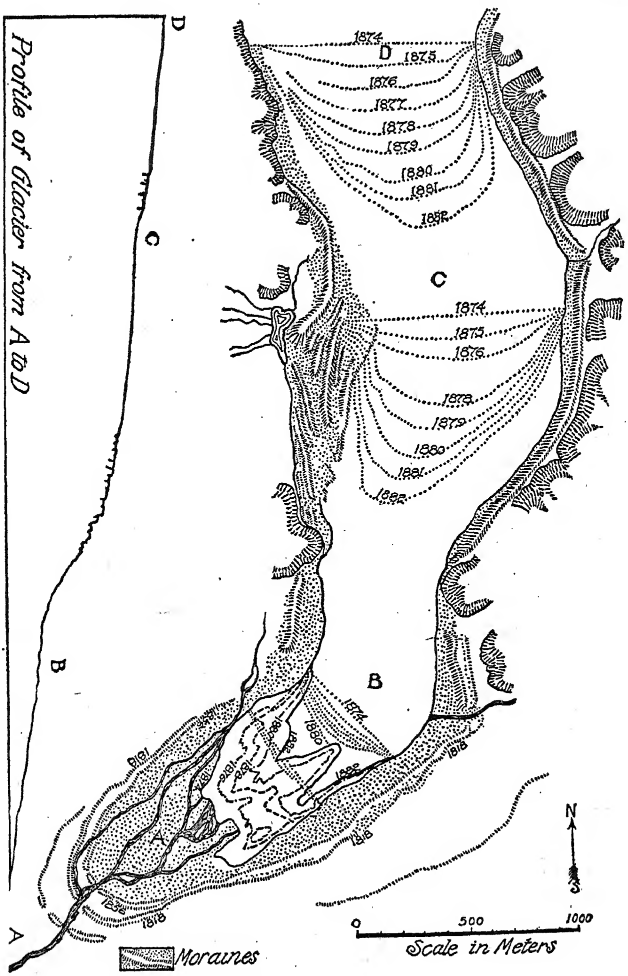


Fig. 313. — Map showing the movement of the ice of the Rhone Glacier in Switzerland, between the years 1874 and 1882 at *B*, *C*, and *D*; the retreat of the ice front by melting during the same period, and the several terminal moraines. (After Heim; from Chamberlin and Salisbury, *Geology*. By permission of Henry Holt & Co.) (See also Figs. 319 *a* and *b*, p. 380.)

than the sides, for the alignment of the stakes, originally straight, became more and more curved downstream at the center. This is well shown in the preceding map of the Rhone Glacier from

which the Rhone River arises (Fig. 313), the movements indicating the advances between the years 1874 and 1882. The fluctuation in the position of the front of the glacier is also shown, and the locations of the terminal moraines at earlier periods are indicated. In general, the rate of movement of Swiss glaciers ranges from one or two inches to four feet or more a day, but glaciers in other parts of the world have shown a greater rate of advance. Thus the Muir Glacier of Alaska (Fig. 314) has moved at the rate of seven feet or more a day, while some Greenland glaciers have

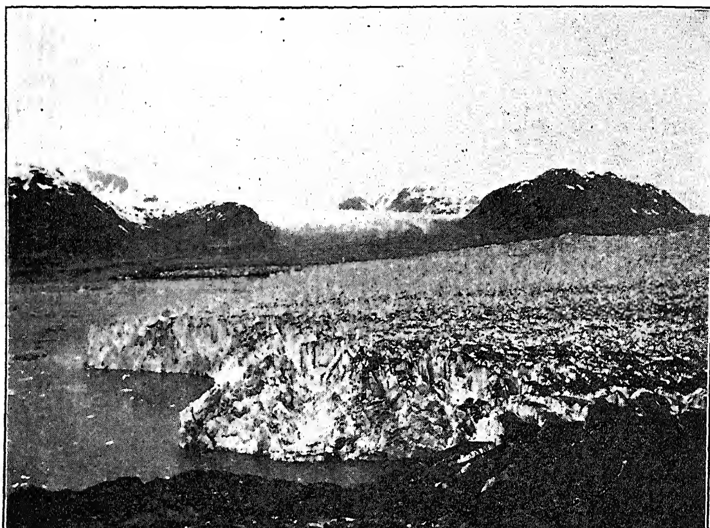


FIG. 314. — Front of Muir Glacier, Glacier Bay, Alaska, from the east. In the distance is Morse Glacier. (U. S. G. S.; courtesy of Prof. D. W. Johnson.) (See also Fig. 318, p. 379.)

moved in summer time as much as 50 or 60 feet a day. These glaciers are, however, of a different type, being tongues from an ice mass of great extent.

The top of the glacier moves, on the whole, faster than the bottom, as was shown by a line of stakes driven into the side wall of a glacier in a favorable spot. Here, after a while, the alignment of the stakes changed from vertical to forward sloping at the top.

Surface Features Due to Ablation. — The surface of a glacier is affected by the heat of the sun and by drying winds, with the result that irregularities are produced by melting and evaporation

When the ice is much fissured by crevasses, as along the outer margins where stresses occur, or where the ice passes over an abrupt change in the slope of the bottom, the melting along these crevasses may produce a rough ridge or pinnacle topography. Where the surface is protected by rocks and other débris of the moraines, which, though absorbing heat on the surface, do not readily conduct it downwards, the surrounding exposed ice will melt more rapidly, leaving the protected portions in relief. A variety of special features may thus be formed, among which ice tables consisting of large blocks of stone supported by ice pillars are perhaps the most striking (Fig. 315).

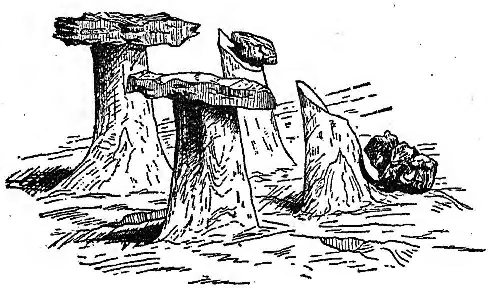


FIG. 315.—"Glacier Tables," ice-pillars protected by slabs of rock. Parker Creek Glacier, California. (After Russell.)

Small stones and dust particles, on the other hand, by absorbing the heat, will cause a more rapid melting and will sink into the ice, forming depressions (dust wells). Thin, bouldery moraines are sometimes sunk below the surface in this manner, whereas a thick moraine comes to rest upon a ridge of ice, and the spreading of the débris down the slope of the ridges may lead to a partial covering of the ice surface, especially in the lower part of the glacier.

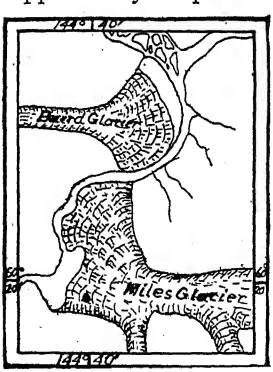


FIG. 316.—Map of Baird Glacier, a typical expanded-foot glacier, and of Miles Glacier, with partly expanded foot and marginal lake formed by expansion of Copper River, Alaska. (After Tarr and Martin.)

The Expanded Foot of Glaciers.—In Arctic regions the valley glaciers continue to the flatter lowland or to the sea-margin, where they expand in a broad, flat lobe, a sort of fan-like ice delta or ice apron, or better, an ice lake without retaining margins. The Foster Glacier of Alaska expands into such a foot on the coast,

and the Baird Glacier of Alaska expands in a similar manner in the valley of the Copper River, which it has pushed to the opposite side (Fig. 316). This is indeed the best known example of such an expanded foot of a glacier. The Miles Glacier, from the opposite side of the same valley, expands in a less regular manner and, moreover, forms a lake of the river along its front. Other examples in Alaska are the Davidson Glacier on the Lynn Canal and the Mendenhall Glacier. When several adjoining glaciers from the same upland coalesce in their expanded portions, the

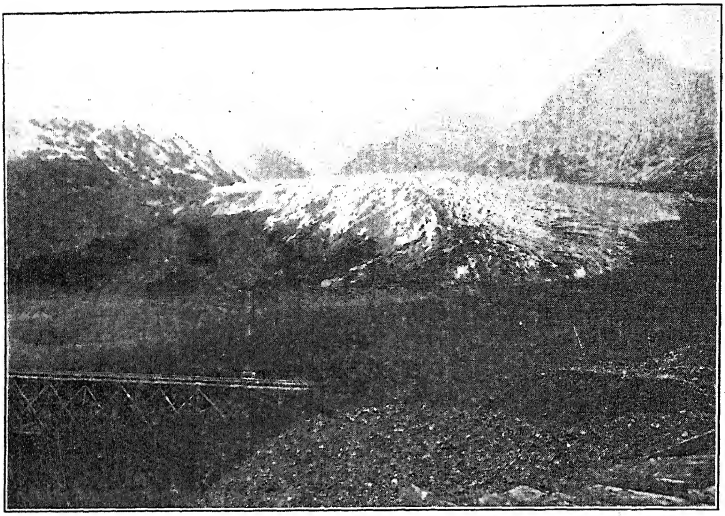


FIG. 317. — Spencer Glacier, Alaska (Oct. 1918). This is melting back and shows a sloping and crevassed front, and a well-developed terminal moraine, especially on the left. (Seward Div. Gov't Railroad; by courtesy Alaska Engineering Commission.)

piedmont type is produced. Conversely, a shrinking piedmont glacier will become resolved into the several component expanded-foot portions of the corresponding glaciers.

Retreat of Glacier Front. — When the rate of melting is in excess of that of advance, the glacier front will move backward or "retreat." The fronts of many Alaskan glaciers have been retreating in recent times, in spite of the fact that the glacier as a whole advances. The front of Spencer Glacier (Fig. 317) is melting away, leaving a part of the valley uncovered. The front of the Muir Glacier (Fig. 314, p. 376), which faces the sea, has

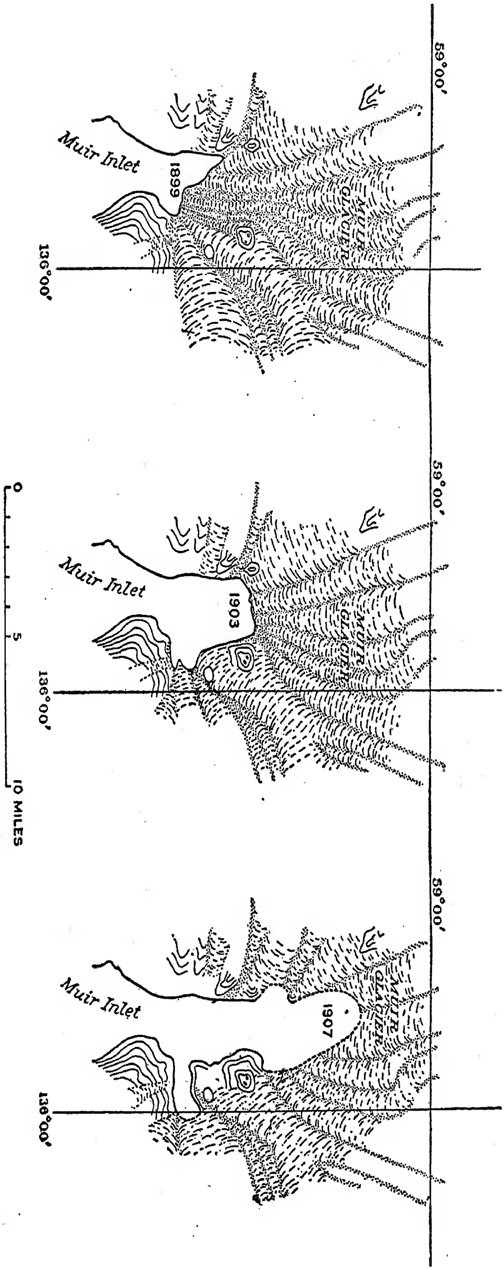


FIG. 318. — Map of Muir Glacier in 1899 (Gilbert and Gannett), in 1903 (Andrews), and in 1907 (Morse and Klotz). In 1911 Tarr and Martin found that the ice front had retreated about 2000 feet more. (U. S. G. S.)

FIG. 319 *a.* — Front of the Rhone Glacier in 1875. (After Walther.) (See also Fig. 313, p. 375.)

FIG. 319 *b.* — Front of the Rhone Glacier in 1900. (After Walther.)

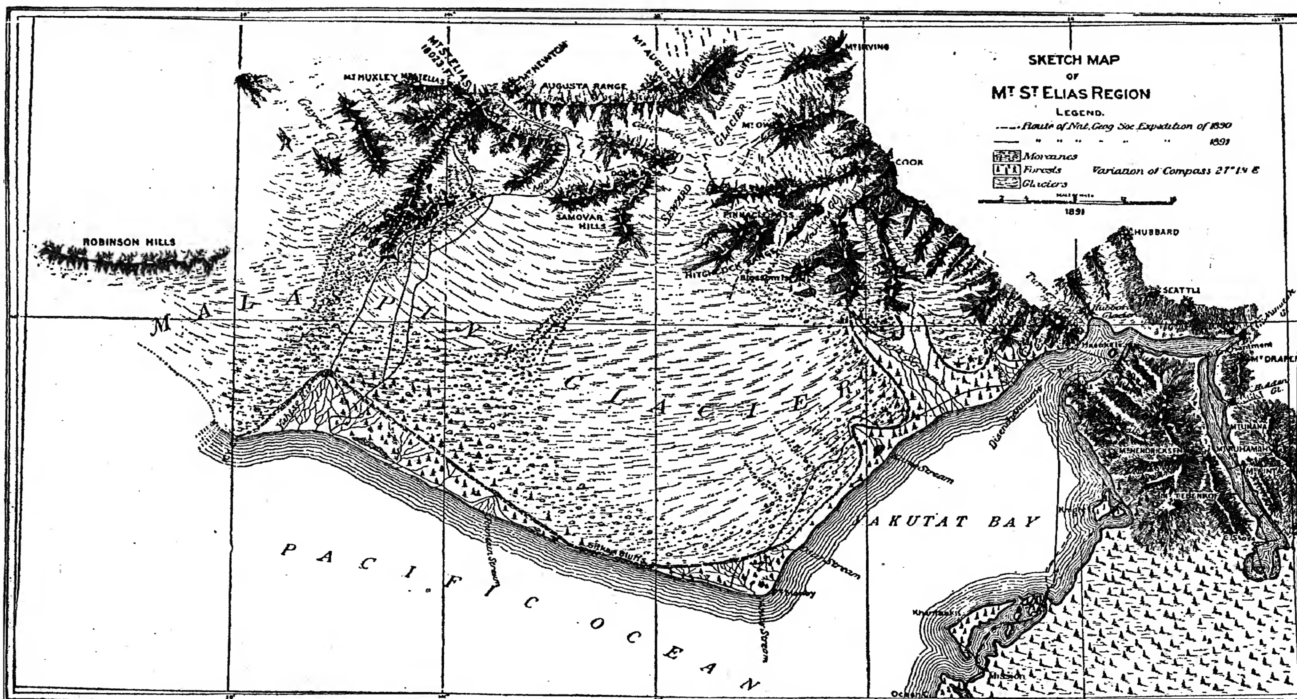


FIG. 320. — Map of Malaspina Glacier and the glaciers of Yakutat Bay, Alaska. Scale 1 in. = 16 mi. (After Russell, *Glaciers of North America*. By permission of Ginn & Co.)

retreated steadily between 1899 and 1911, the retreat between 1907 and 1911 being 2000 feet. The positions of the front in 1899, 1903, and 1907 are shown in the diagrams (Fig. 318, p. 379). In the next two figures the change in the front of the Rhone Glacier is shown between the years 1875 (Fig. 319*a*) and 1900 (Fig. 319*b*). In speaking of the retreat of the glacier we must remember that it is the front of the ice which alone changes its position, not because the glacier as a whole moves backward,

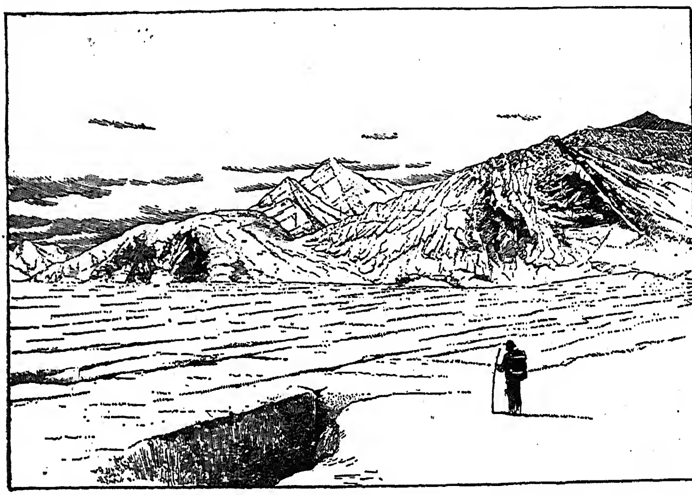


FIG. 321. — Surface of Seward Glacier, Alaska. The summit of Mt. St. Elias is seen in the distance beyond the hills bordering the glacier. Drawn from a photograph. (After Russell, *Glaciers of North America*. By permission of Ginn & Co.)

but because it melts away at the front. The water resulting from the melting forms the glacial stream, while the rock débris, which was carried in and upon the ice, remains behind and forms the terminal moraine. (See further, Chapter XVI.)

The Piedmont Type of Glacier

The Malaspina Glacier. — At the foot of Mount St. Elias and west of Yakutat Bay in Alaska lies the Great Malaspina Glacier or ice fan which, with its moraines and secondary deposits, here forms the border of the North Pacific Ocean (Fig. 320). This ice-mass is formed by the confluence of the basal expanded portions of a number of valley glaciers which descend from the mountainous

regions, the largest of these being the Seward Glacier (Fig. 321), while others are the Agassiz and the Tyndall glaciers.

The surface of the Malaspina Glacier has an exceedingly gentle slope, while the mass as a whole is relatively stagnant. Its area is about 1500 square miles (about the size of Rhode Island) and its marginal thickness perhaps 1000 feet. Along parts of the foot of the Malaspina Glacier an extensive terminal moraine is de-

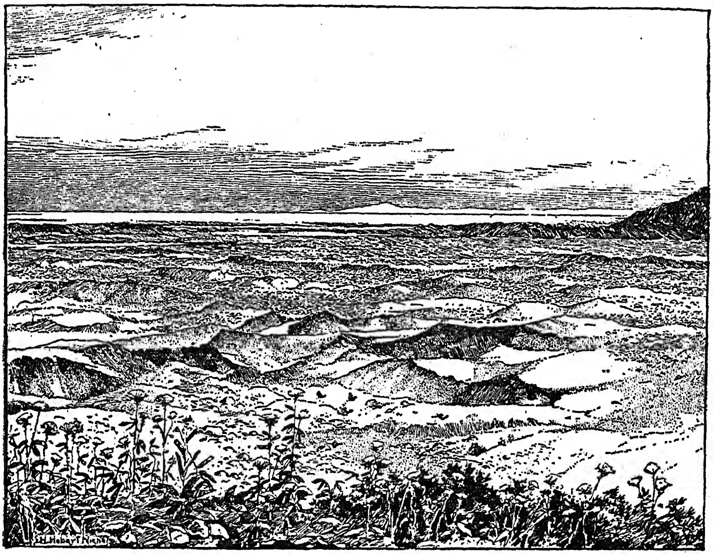


FIG. 322. — Moraine-covered border of Malaspina Glacier from Blossom Island. Drawn from a photograph. (After Russell, *Glaciers of North America*. By permission of Ginn & Co.)

veloped, while other parts deploy into the sea and from them fragments are broken off to form icebergs. In some portions where the partial melting of the ice surface has permitted the accumulation upon the ice of a mantle or covering of débris (Fig. 322) a luxuriant vegetation has sprung up, and in places this glacier actually supports a forest growth (see map, Fig. 320) with trees, some of which have reached a trunk diameter of three feet. In many places stagnant pools of water occur in which sediments are deposited, while over the central portion, where débris is absent, there are many crevasses into which fall the streams from the melting ice. Glacial streams issue from tunnels beneath the ice in several places (Fig. 323).

Other Piedmont Glaciers. — Other examples of piedmont glaciers are Bering Glacier, west of the Malaspina, and of about the same size, and the smaller Alsek Glacier to the east. In Chile,

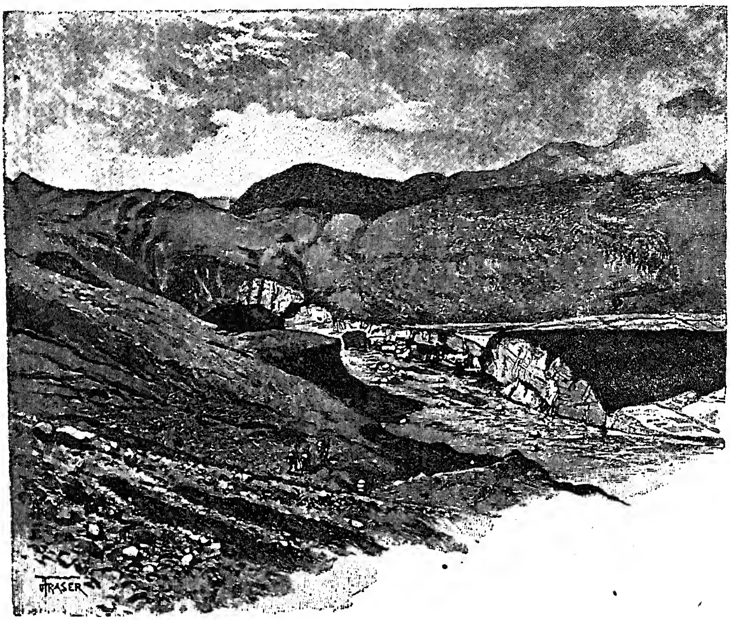


FIG. 323. — Entrance to ice tunnel in Malaspina Glacier. Drawn from a photograph. (After Russell, *Glaciers of North America.* By permission of Ginn & Co.)

south of S. lat. 42°, lie the San Rafael piedmont glacier and some others. Piedmont glaciers also existed in the Alps and in the Rocky Mountains during the Pleistocene period, as is shown by the abandoned moraines and other features.

ICE-CAPS

The Vatna Jökull. — In the southeastern part of Iceland lies the plateau of Vatna Jökull, the largest of the many ice-covered plateaus or jökulls found in that northern island (Fig. 324). It has an area of 8500 square kilometers, being covered throughout by an ice-cap which forms an arched dome with slopes descending from 1900 meters in the center to 800 meters near the margin, where it sends out ice tongues to the lower levels (20 to 100 meters). As

there are few or no projecting rocky peaks rising through it (except near the margins) this ice-cap is largely free from débris and very white. Iceland has several such ice-caps and they form a transition to the more extensive inland ice mass, such as that of Greenland.

Other Examples. — Similar caps or plateau glaciers are found in Scandinavia, but these are smaller and often elongated; they also send out tongues in all directions. The ice mantle of Red

FIG. 324. — The Ice-Cap of Vatna Jökull in Iceland. Ice in black. (After Th. Thoroddsen, *Petermann Mitt.* 1906.)

Cliff Peninsula, north of Inglefield Gulf in Greenland, is another example, and still others are found in the Kerguelen Islands, and on the summit of Kilimandjaro in Africa. All such ice-caps imply conditions of exceptional precipitation and, on the whole, low temperatures.

CONTINENTAL GLACIERS

The Greenland Ice Cover (Fig. 325). — Related to the preceding type, but of vastly greater extent and thickness, is the ice mantle which covers Greenland. This is believed to have the character of a very flat dome, the highest portion of which lies somewhat to the east of the median line of the continent, and the thickness of which approximates perhaps 3000 feet. It forms a continuous mantle, except for a narrow marginal portion in which the underlying rocks are exposed, this portion varying in width from five to twenty miles, though in places the ice reaches the coast. In two

localities, however, the uncovered margin reaches a width of from 60 to 100 miles.

Only the northern and southern portions of this ice field have been crossed, the great central area being entirely unknown, but there is little reason to think that it is other than a vast field of snow and ice. In this central portion the surface is probably nearly flat, rising perhaps 10,000 feet above sea-level. Around the margins, however, for a width ranging from 75 to 100 miles, the outward slope is rather abrupt, often being so steep as to be difficult of ascent. This slope is broken into a series of broad terraces or steps, though the rock margins of the continent, where uncovered, are generally mountainous, reaching heights between 5000 and 8000 feet on the east coast, but not over 6000 feet on the west. Within the margin of the ice, high rock peaks occasionally project through it, forming *nunataks*. From the margin of the ice mass many tongues and lobes project outward into the valleys of the coastal region.

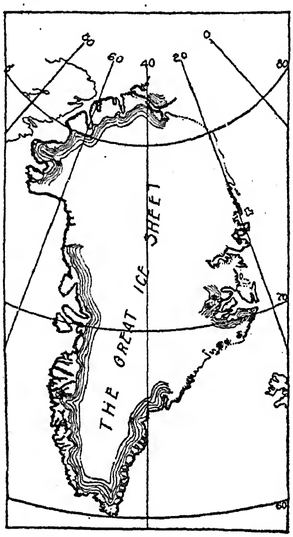


Fig. 325. — Map of the Greenland Ice-Cap. (After Stieler; from Chamberlin and Salisbury, *Geology*. By permission of Henry Holt & Co.)

The edge of the ice mass, where not extended in glaciers, is often very precipitous or even overhung by an ice cornice. This is most marked in northern Greenland, but becomes the exception farther south. Crevasses are common in some parts of the surface of the marginal portion, and many dimples and "basins of exudation" occur in some sections above the margin.

Where the ice moves outward between adjoining nunataks, a series of crescent-shaped moraines of débris is often formed, these moraines extending from one nunatak to another and having their convexity pointing outward. These are held to be formed by material carried up from the lower or basal portions of the ice, the upward movements being produced by the formation of curved shearing planes due to obstructions, and the outward convexity to the accelerated motion of the central portion of the ice

between the nunataks and marginal retardation by them. The nunataks themselves furnish only minor amounts of débris to the surface of the ice, though in some cases morainal ridges extend from them marginward.

The chief portion of the ice which encloses rock débris lies within the basal 100 feet of the masses exposed in the sections. Here much englacial material is found, and this appears to be largely derived from the bottom of the ice sheet and carried upward by obliquely outward-rising shearing planes. In many portions along the margins heavy terminal moraines accumulate, being chiefly derived from the subglacial and englacial material brought there by the outward moving ice.

Comparatively little water issues from the margins of the ice-sheet of Greenland, though small streamlets appear beneath the ice border, bringing sand and gravel which they distribute among the coarser morainal material.

The Antarctic Ice-Sheet. — The Antarctic continent, which is larger than Europe, is covered by a great ice-sheet similar to that which covers Greenland, and which like the latter is dome-shaped, with a height of 10,500 feet above the sea at the pole (Amundsen). Many great mountain masses or nunataks project through the ice, rising to heights of 15,000 feet. Along the margin the ice-sheet sends out valley glaciers which reach the sea, while part of the great sheet itself abuts upon the ocean as in the case of the floating ice shelf or Great Ice Barrier of Victoria Land, with ice-cliffs many miles in length and in places rising to heights of 280 feet, though elsewhere low enough to permit landing from a ship alongside of it.

Icebergs

Where glaciers enter the sea or other water bodies they advance on the bottom until a depth equal to their thickness is reached, when portions are detached from their front and float away as icebergs (Fig. 326). Such icebergs may become tilted or even over-

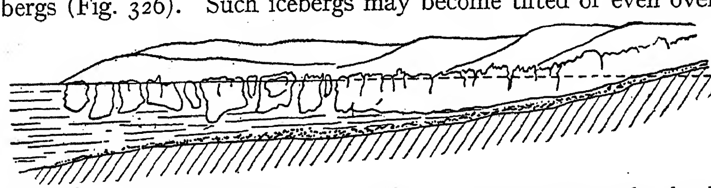


Fig. 326. — Glacier descending into the sea, where its front is buoyed up by the water and becomes broken up into icebergs. (After A. Helland.)

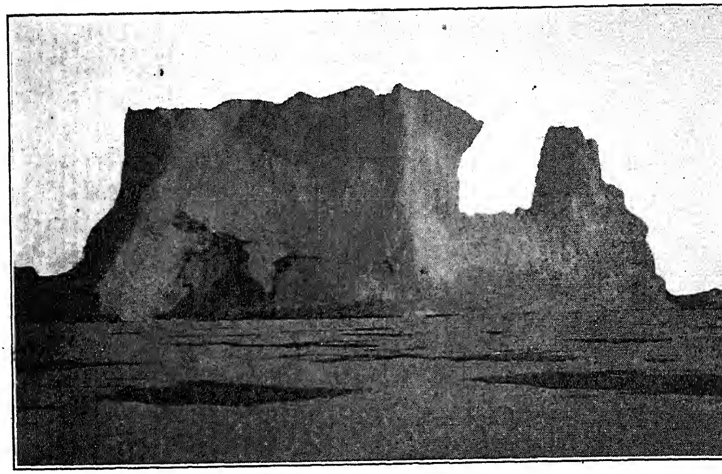


FIG. 327 *a*. — A large iceberg.

turned, and they soon lose their load of débris. In some cases, however, this may be carried far to sea before the melting of the iceberg permits its deposition on the bottom. In certain cases where many successive icebergs melt near the same point, submarine banks composed of ice-rafted material may be built up. The Grand Banks off Newfoundland have been regarded as in part, at least, formed by such débris.

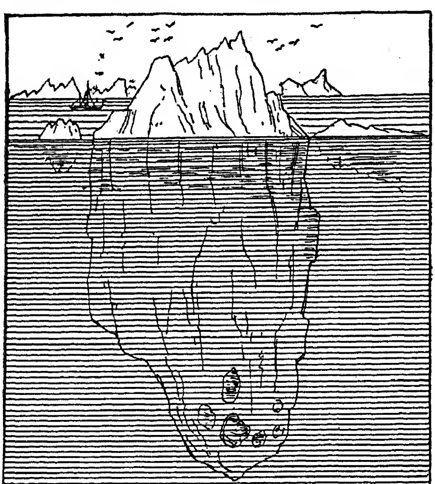


FIG. 327 *b*. — Floating iceberg, showing the proportion of visible to submerged ice. (From Kayser's *Lehrbuch*.)

Only a small portion of an iceberg (in pure ice only one ninth) appears above water (Figs. 327 *a*, *b*), and while icebergs from Greenland seldom exceed 100 feet in exposed height, some in the Antarctic region have been found to rise 500 feet or more, with a length of several miles. This would make these bergs blocks of enormous size.

Causes of Ice Movement

The subject of the causes of glacial movements belongs to physics rather than to geology, but may be briefly considered. By many (following Forbes) ice has been considered a viscous substance which in large masses will flow under the influence of its own weight like pitch or asphalt. Freezing of descending waters and the consequent expansion was regarded by Agassiz and Charpentier as the chief cause of glacier motion. Partial melting and refreezing within the mass, the momentary liquefaction of minute portions of the mass while the ice as a whole remains solid, — may produce a condition of flowage of the ice. This melting may be the result of pressure rather than applied heat. Expansion and contraction have also been appealed to and so have repeated fracturing and refreezing (regelation). Finally, the growth of the ice crystals themselves has been invoked, and the influence of gravity no doubt is effective in glaciers upon a sloping surface. Altogether the subject is too complicated for elementary treatment, and we may merely remark that different combinations of the above mentioned causes, and perhaps others, are effective in producing the movement of different glaciers and perhaps of the same glacier at different times.

CHAPTER XV

DESTRUCTION OF ROCKS AND THE FORMATION OF CLASTIC MATERIAL

ALL rocks are subject to destruction, and the product of such destruction may be visible fragmental or *clastic* material, or it may be changed by great heat into molten material (*magma*), or finally it may be invisible as the result of solution in water, or of vaporization. Molten, dissolved, or vaporized rock material will be redeposited under favorable conditions as igneous rock, as aqueous precipitates, or as gaseous sublimates (sulphur, etc.), respectively, or, by the intervention of animals and plants, as organic deposits. Fragmental material, on the other hand, will produce, when reconsolidated, a new type of rock, the *clastic rock*, and to this attention is now invited.

AGENTS ACTIVE IN THE FORMATION OF FRAGMENTAL OR CLASTIC MATERIAL

In general, we may note that there are two methods of breaking rocks into fragments, the chemical and the mechanical. In the first case, the fragmentation is produced by alteration of the material of the rock, either by abstraction of some of the component material, in solution, etc., or by the addition of material such as oxygen, water, carbon dioxide, etc., or by both. The chemical method of rock-breaking is called *decomposition*, and the products of decomposition differ from the material of the original rock. In the second method of rock-breaking, the mechanical, the rocks are merely broken into fragments, or are separated into their component minerals. This is called *disintegration*. When both modes of change go on together, under the influence of the atmosphere and its contained water vapor and gases, with accompanying temperature changes, etc., the process is called *weathering* of rocks.

The agents active in the production of fragmental material from the rocks of the earth's crust, are the following:

1. **The Atmosphere.** — This operates by the action of its constituents, its contained gases and vapors, by its transmission of the heat of the sun, and the escape, by radiation, of the heat waves from the earth, and by the mechanical action of wind.

2. **The Hydrosphere.** — This operates by solution of rock and alteration of its constituents, and by mechanical activities of its movement, as in the case of waves, river-currents, rains, etc.

3. **The Pyrosphere.** — This agent operates chiefly through igneous explosions, which shatter the rock.

4. **Movements of the Lithosphere.** — The grinding and fracturing of rocks in the movement of one rock mass over or against another, as in faulting, represent the chief work of this agent. Here also are properly placed the movements of large ice masses, such as glaciers, over other rock surfaces, and their destructive work.

5. **The Biosphere.** — This operates by various rock-destroying activities of plants and animals, including man.

Processes of Erosion

Breaking up or fragmentation (clastation) of rock is one form of *erosion*, and the product of such work in general remains near the scene of operation unless other agencies are active. Erosion is, however, accomplished in another manner, namely by the breaking off and removal of material by the agent of erosion. This is called *ablation*, and also becomes the first step in the transportation of material. Ablation may be effected mechanically by the denuding or stripping of the surface of material loosened by processes of clastation or rock-breaking in place. Such removal is called *denudation*. A second process is that of *corrasion*, where material is ground or filed away by means of " tools " which are carried by the agent. Thus wind carrying sand grains or dust will corrade any surface over which it blows, after the manner of the artificial sand blast used in renovating old stone structures, such as the stone fronts of buildings, etc. The wear which these sand grains themselves experience is call *abrasion*. A third method is analogous to quarrying by man, in that, by a process of undermining and loosening, large masses of rock are removed from their original location. Finally, chemical ablation takes place, when the rock mass under-

goes solution, melting, or other chemical change which at the same time removes the material. This is expressed by the general term *corrosion.* It is sometimes spoken of as chemical denudation. We may tabulate these processes as follows:

Erosion

- I. *Fragmentation* or *clastation.* — Breaking or shattering material *in situ* not necessarily accompanied by removal.
  - (*a*) Physical, or disintegration.
  - (*b*) Chemical, or decomposition.
- II. *Ablation* or the separation and simultaneous removal of rock material by the same agents.
  - (*a*) Mechanical
    - 1. Denudation.
    - 2. Corrasion and abrasion.
    - 3. Quarrying.
  - (*b*) Chemical
    - Corrosion.

Destructive Work of the Atmosphere

Weathering

By weathering we understand all the rock-modifying influences of the atmosphere, other than the mechanical activities of the wind. These weathering processes are both chemical and mechanical and belong primarily to the division of rock-breaking or clastation, though some corrosion may also occur.

Daily and Seasonal Changes of Temperature; Insolation. — All rocks are affected to a greater or less degree by the daily and seasonal changes in temperature, and although the source of the heat which affects the rocks is the sun, the presence of the atmosphere modifies this, so that the effects or changes produced are properly classed with the activities of the atmosphere. In common with nearly all substances, rocks expand under the influence of heat and contract under that of cold. Illustrations of the expansive effect of the sun's heat on substances are seen in the lengthening on hot summer days of the rails on a car track, which are purposely placed short of contact to allow for such expansion, which would otherwise cause a buckling of the rails. On very cold days the ends of the rails are separated by an appreciable gap. The buckling of concrete sidewalks from prolonged exposure to the sun is another example, and the repeated removals of such bucklings and filling of the gaps with new cement is necessary, and noticeable in most older cement walks. The chief effects produced on rock masses by these changes in temperature are exfoliation and granular disintegration.

Exfoliation. — Where changes of temperature between day and night are great, as in desert regions, the effect upon the rocks is very marked. During the day the exposed rock surfaces are intensely heated, especially in the case of the dark-colored igneous rocks, which absorb more heat than those of lighter color. The daily range in temperature on the surfaces of some rocks has been estimated as high as 80° C. (144° F.). As rock, on the whole, is a poor conductor of heat, the surface is chiefly affected, though the heat passes gradually inward. Hence the surface layers are subjected to an expansive force, while the deeper layers are not so affected. On cooling by radiation in the clear atmosphere, the temperature of the outer layers will sink rapidly and may easily pass below that of the inner part of the rocks. As a result, the surface portion for some distance inward is subjected to a series of strains which will result in the flaking or peeling off of such outer layers. As the angles of rocks are most exposed, being subjected to heating from all sides, they will fall off first, and the

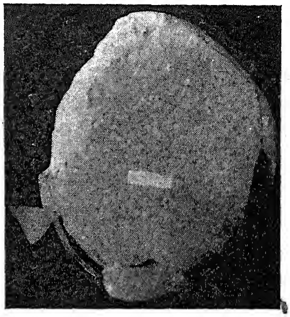


FIG. 328 *a.* — Concentric exfoliation in a fine-grained basic igneous rock. Note the successive shells which are peeling off. (From specimen in Columbia University. B. Hubbard, photo.) Reduced.

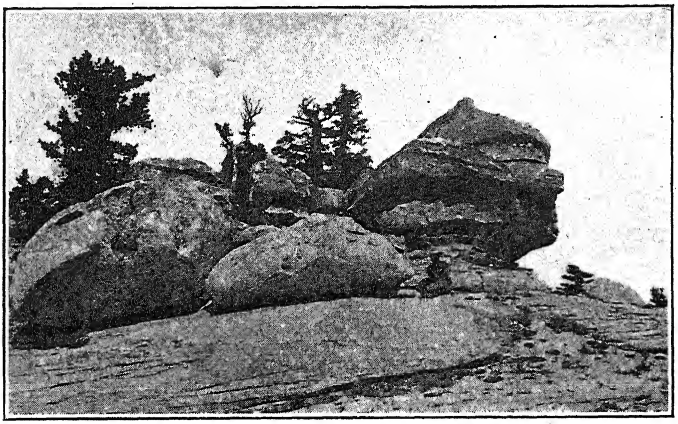


FIG. 328 *b.* — Concentric exfoliation or "spalling" of biotite granite. Ridge south of Morrison Creek, Yosemite Quadrangle, Cal. (Photo by Turner, from U. S. G. S.; courtesy of *Popular Science Monthly.*)

result will be the production of a curved or rounded outline, and the subsequent layers peeled off will also be curved. Thus *concentric* exfoliation or the successive peeling off of layers of rock results, a phenomenon very marked in most dark and fine-grained rocks in such regions (Figs. 328 *a–c*). When the changes in temperature and the consequent expansion and contraction are very rapid, large masses of rock may be thrown off with some violence. Over large, nearly flat surfaces, the effect of insolation is such as to produce a series of planes of separation parallel to the surface

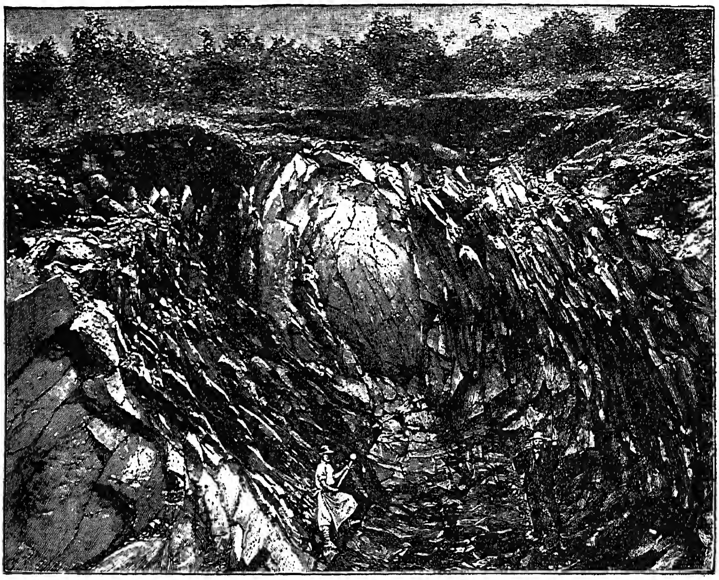


FIG. 328 *c.* — Concentric exfoliation in a dike of basic igneous rock. (From Ratzel, *Die Erde.*)

and at progressively greater distances apart in depth. Such expansion joints or planes are seen in the faces of most granite quarries, and they greatly facilitate the process of quarrying, but limit the size of the blocks obtainable near the surface (Fig. 329).

Granular Disintegration. — Besides affecting the rock mass as a whole, changes in temperature have a further detailed effect upon the minerals or particles of which the rock is composed, especially if, as is usually the case, these are not all of one kind. A granite, for example, exposed to such influences, will have its several minerals affected in different degrees. The dark minerals (horn-

blende, black mica) will absorb heat more readily and also give it up more quickly than the light minerals. Moreover, the ability

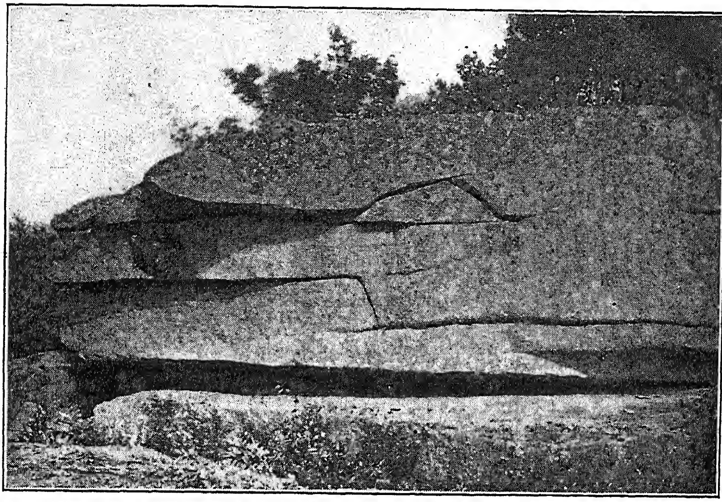


FIG. 329. — Horizontal jointing in a granite ledge, due to expansion and contraction of the surface layers under insolation. (Courtesy of Prof. J. B. Woodworth.)

to react to heat and cold is not the same in the feldspar as in the quartz, and both differ in this respect from the dark minerals. In other words, each mineral has its own coefficient of expansion and contraction. As a result, internal stresses are set up and the minerals will tend to separate one from the other and finally fall apart, producing a sand of loose minerals. This *granular disintegration*, as it is called, — the separation of the rock into its component minerals, — is a characteristic feature observable in all granite and similar rock

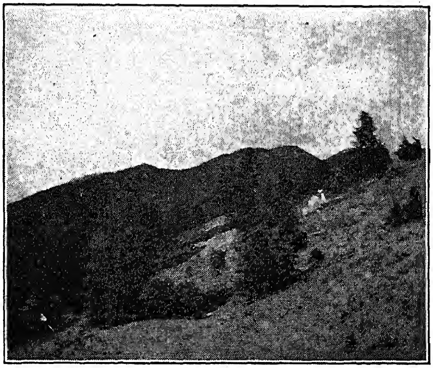


FIG. 330 *a*. — Slopes of crystalline sand on the sides of Pikes Peak, Colorado. The sand is the product of granular disintegration of the granitic rock, and consists of quartz, feldspar, and ferro-magnesian mineral fragments. (Photo by the author.)

masses. The slopes of Pikes Peak, which is a mountain largely composed of coarse granite, are covered with long screes of such disintegration products, which have the appearance of a coarse sand with a smooth surface which slopes at the angle at which such material will come to rest, that is, the *angle of repose* (Fig. 330 *a*). Similar products of granular disintegration may be seen around large granite boulders on exposed hillsides, even in fairly moist regions (Fig. 330 *b*). Such boulders are themselves often the product of granular disintegration (Fig. 330 *c*). Granite surfaces often show areas of bare rock separated by fissures, into which the product of disintegration has

FIG. 330 *b*. — Disintegrating granite boulder, Dogtown Common, Cape Ann, Mass. Half of the boulder has crumbled into crystalline sand. (Photo by the author.)

FIG. 330 *c*. — Granite boulders, the result of decomposition and disintegration of granite *in situ*; resting on granite ledge. Graniteville, Mo. (Gardner collection of photographs, No. 7908. Courtesy Geol. Dept., Harvard University.)

been washed by rains, and here, in the moister climates, where this material is further decomposed, lines of vegetation will spring up. In moist climates, dark igneous rocks are often reduced to a mass of residual boulders by combined disintegration and decomposition (Figs. 331 *a*, *b*).

FIG. 331 *a*.—Boulders of disintegration and decomposition. Part of a Camptonite dike weathered until only scattered residual blocks of the original rock remain.

Finally, it should be noted that the minerals themselves are affected by these temperature changes, because minerals with several distinct crystal axes react differently on the several faces. Thus a crystal of feldspar is itself subjected to internal stresses which open

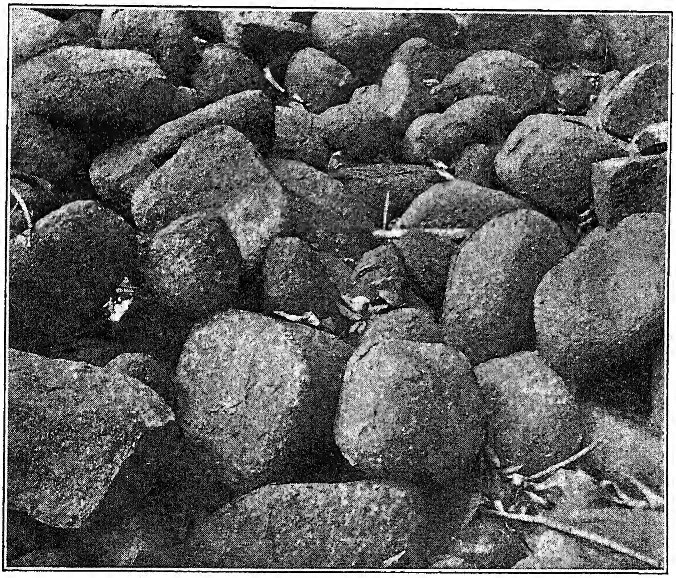


FIG. 331 *b*. — Boulders of disintegration. Residual masses left by weathering of a diabase dike, Medford, Mass. The dike had been left in relief by quarrying operations, and weathered into a mass of spheroidal boulders. As the dike finally crumbled completely, the boulders were thrown together into the heap here shown. (Photo H. W. Dyer; courtesy of Prof. Elizabeth Fisher, Wellesley College.)

minute fractures along the cleavage lines. Into these fine fractures air and moisture will penetrate and effect the decomposition of the mineral along the sides of the fracture.

The Talus Slope (Fig. 344). — By the disruption and disintegration of the rock masses, loose material of all sizes is formed, and this will accumulate at the foot of every cliff, forming a *talus*, the surface slope of which varies with the coarseness of the material. In dry climates, the talus is chiefly formed by the processes above described, but in cold climates where the atmosphere is moist, frost action may become an important factor in its production. By the combined action of these agencies it is brought about that most exposed mountain peaks are heaps of coarse, loose material, generally burying the ledges, while long slopes of finer material are formed in every favorable locality.

Land Slides. — When a talus slope becomes saturated with rain-water during a moist season, its potential angle of slope is lowered, because the entire mass becomes more mobile than when dry. For a time, the angle of slope may be maintained, but at a critical moment the cohesive force may be overcome and the entire mass, or a large part of it, will slide down the mountain's slope, forming an earth and rock avalanche or rock slide (Fig. 332), which may produce disastrous effects in the valley bottoms below, destroying farmlands and buildings, and damming narrow valleys so that the upper portions may be converted into closed basins in which lakes will form. By the final overflow of the lake-water, and the accompanying destruction of the earth dam, disastrous floods may sweep the valley below. In one of the upper branches of the Ganges River in the Himalayas, a slide, bringing down 800,000,000 tons of rock débris in three days, built a dam across the narrow valley nearly a thousand feet deep. Be-

FIG. 332. — Land-slide, Ausable Lake, N. Y. (A. D. Savage, Photo.)

hind this a lake accumulated, reaching a length of four miles in a year. Then the overflow partly destroyed the dam, allowing 400,000,000 cubic yards of water to discharge in about four hours and flooding the valley below to a depth of 100 to 170 feet, destroying every vestige of habitation for a distance of 150 miles down the valley. Even on gentle slopes the saturation of the talus by water will produce disastrous slides.

FIG. 333. — The Old Man of the Mountain, Franconia Notch, White Mountains, N. H. Illustrating peculiar result of rock weathering.

Frost Work. — Water on freezing expands one tenth of its volume and so becomes a powerful agent in disrupting rock. Where the moisture of the air is condensed on the cold surfaces of rocks, long ice crystals may form, and if these develop in crevices, their growing force pushes the walls apart and eventually loosens the smaller fragments, which then fall to the bottom of the cliff to aid in building the talus. By the combined action of frost and insolation remarkable erosion forms may be produced, an example of which is seen in the "old man of the mountain" in the White Mountains (Fig. 333).

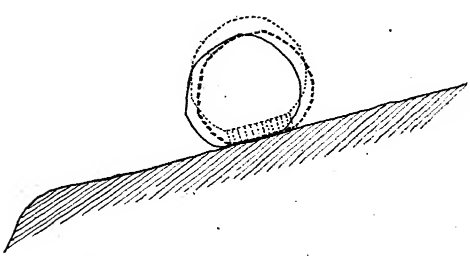


FIG. 334. — Diagram showing three stages in the downward progress of a boulder on a sloping hillside under the action of frost. The original position is shown by heavy dotted lines. Frost crystals forming under the boulder raise it at right angles to the surface (fine dotted lines); when these supporting crystals melt the boulder settles back at right angles to the horizon (solid outline).

Boulders on a rock or other hard surface are often lifted to a slight degree by the formation of innumerable ice crystals beneath them. If the

surface on which the boulder rests has a slope, lifting by the crystals will be at right angles to this slope. On the melting of the ice, the boulder will settle back vertically, and thus make a slight advance down hill. In this manner a large boulder may travel for considerable distances down hill in the course of time and may eventually reach the edge of a precipice over which it will finally fall (Fig. 334).

Frost acts in a similar manner on pebbles and on the finer material which forms the soil. The effect of the frost upon the soil

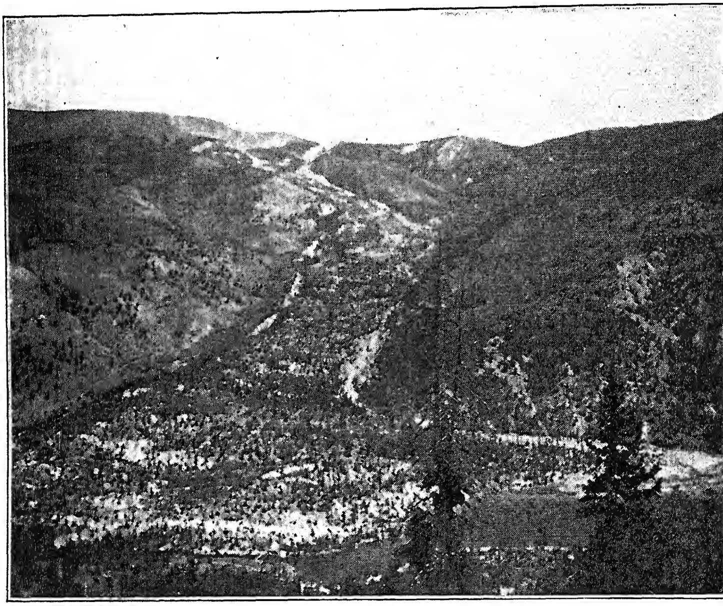


FIG. 335. — View of the Slumgullion rock-flow from its source to Lake San Cristobal, which was formed when the great slide dammed up the river valley. (Photo by W. Cross, U. S. G. S. Courtesy of D. W. Johnson.)

is one of expansion, by filling it with ice-crystals, which lift and push apart the particles. This may readily be seen in dirt paths on a frosty morning, in the spring or autumn. When the ice crystals melt, they leave the soil full of small cavities which give the mass a loose spongy character. Under the beat of the rain, the running and soaking in of water, the movement of the groundwater, the trampling of animals, etc., this uplifted, loosened soil is again compacted, and in this process slowly moves down hill.

By the alternate freezing and thawing of the moisture in a talus slope, this may undergo a slow process of creeping down-hill, forming a "rock glacier" (Figs. 335, 336). Such creeping talus masses, often of considerable length, have been found in many mountain regions where intense cold prevails for part of the year. Their movement is often indicated by the complete absence of vegetation, even over the lower, gentler slopes, plants being unable to maintain a foothold on account of the motion.

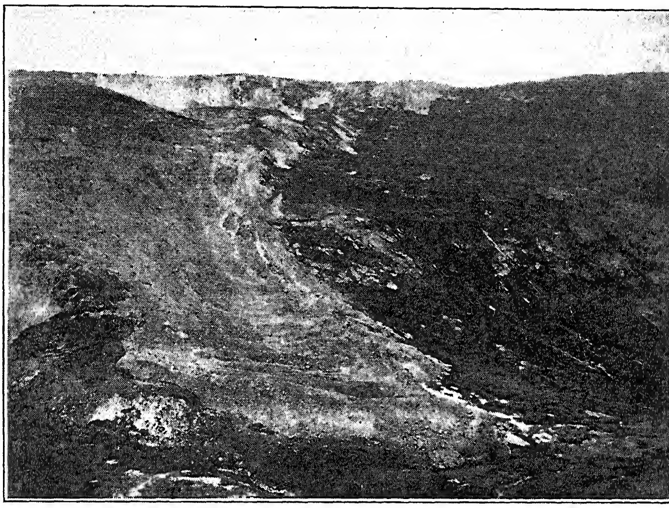


FIG. 336. — View northeast across Cleveland gulch at landslide mass and conglomerate rock-glacier. Silverton Quadrangle, Colo. (Willis, Photo; from U. S. G. S.)

Soil on hillsides also creeps under the influence of freezing moisture, as well as gravitative control, and this creep is well seen where the underlying rock is exposed in cuts or otherwise, and where it is composed of vertical or steeply inclined beds, especially shales or schists. The upper ends of these beds below the soil are then frequently found bent forward as the result of the dragging effect of the creeping soil (Fig. 337).

Chemical Work of the Atmosphere. — The atmosphere consists of a mixture of oxygen and nitrogen, the former being somewhat less than 21 per cent of the volume, and the latter something over 78 per cent. Besides this, there is a small quantity of the element argon and other rare gases (less than one per cent by volume) and

a fairly constant admixture of carbon dioxide (CO_2, about 0.03 per cent by volume) and water vapor (H_2O) in very variable quantity. Minute quantities of other compounds, such as ozone, nitric acid and ammonia, are also found, together with free hydrogen, sulphur compounds and other substances. The agents active in producing chemical changes in the rock are, however, few, comprising chiefly oxygen, carbon dioxide and water vapor. Accordingly the chemical activities of the atmosphere may be grouped under (*a*)

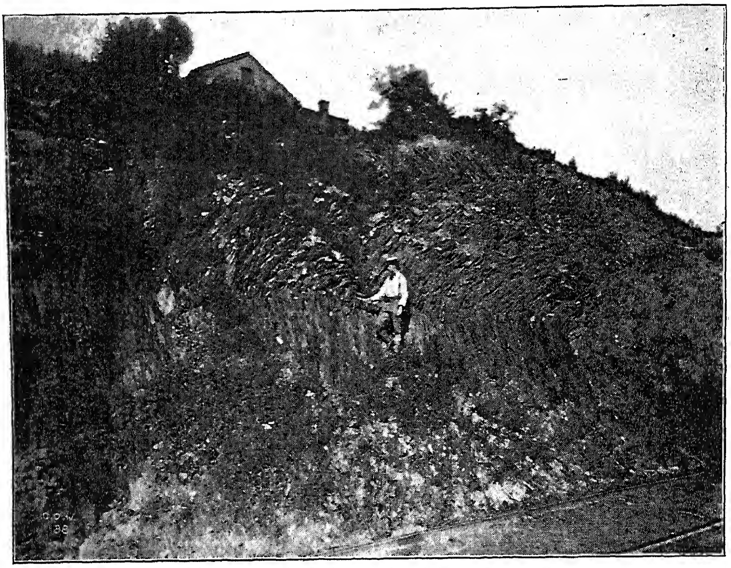


FIG. 337. — Nearly vertical beds of shale bent over and broken at the top, by superincumbent weight, or creep of the overlying soil. Columbia, Pa. (Walcott, Photo U. S. G. S.)

oxidation, (*b*) carbonation and (*c*) hydration and dehydration. Special combinations of these produce other changes such as kaolinization and laterization.

Oxidation. — The oxygen of the air accomplishes its chief work by uniting with the iron and sulphur of the rock-forming minerals and with the organic matter present. This is called *oxidation.* The iron of the ferro-magnesian minerals and of other iron compounds in the rocks is transformed into the oxide (Fe_2O_3), or in the presence of moisture into the hydrous oxide of iron. The former has a red color (the mineral hematite, etc.) and the latter a yellow or ocher color (limonite, etc.). In their formation there is generally an increase in volume of the material, this being especially great when limonite is formed by simultaneous oxidation and hydration. When magnetite (Fe_3O_4) is

altered to limonite by these processes, the increase in volume is 64 per cent. On the other hand, if iron carbonates are oxidized, the loss of carbon dioxide is not wholly compensated for by the addition of oxygen and water, and the volume decreases. By the oxidation of the sulphur of the rock minerals, such as pyrite, both sulphurous and sulphuric acids may be formed, which unite with the iron or other substances to form new compounds (sulphites and sulphates). By the oxidation of the organic matter, carbon dioxide (CO_2) and water are produced.

Carbonation. — This most commonly affects the silicate minerals, the carbon dioxide combining with the basic elements to form carbonates, while silica is set free. Besides the carbon dioxide of the atmosphere, there is generally an abundant supply of this gas furnished by the oxidation of the organic matter, and this also becomes active in attacking the rock, altering some of the minerals. Water takes up carbon dioxide, from the air, and from decaying organic matter in the soil and in stagnant ponds; indeed more CO_2 is obtained from organic matter than from the air. Water thus charged with CO_2 is a powerful solvent, attacking and dissolving many minerals. We shall return to this subject in the study of groundwater.

Hydration. — This is the union of water with the mineral substances of the rocks and is the most important single process of change, but hydration by atmospheric moisture is only a superficial process often associated with oxidation. More effective, however, is the hydration due to the circulation of ground-water in the pores of the rock. Hydration causes the expansion of the minerals, forming stresses in the rock, which lead to its crumbling. As the most important single example of hydration is the changing of feldspars to kaolin or clay, we will consider this and the related process of laterization more in detail.

Kaolinization. — We have seen that feldspars are apt to be traversed by numerous fine fissures due to the influence of heat and cold. Moisture entering these in the presence of carbon dioxide changes the feldspar to clay or kaolin, which may be seen in a thin slide as a clouding of the otherwise transparent mineral, along the sides of the cleavage lines.[1] Complete change to kaolin (clay) occurs in time, according to the following chemical reaction:

$$\underset{\substack{\text{Orthoclase}\\\text{feldspar}}}{2\,KAlSi_3O_8} + \underset{\text{Water}}{2\,H_2O} + \underset{\substack{\text{Carbon}\\\text{dioxide}}}{CO_2} = \underset{\substack{\text{Kaolin}\\\text{or clay}}}{H_4Al_2Si_2O_9} + \underset{\text{Silica}}{4\,SiO_2} + \underset{\substack{\text{Potassium}\\\text{carbonate}}}{K_2CO_3}.$$

In this change from feldspar to kaolin or pure clay, there is a decrease in volume of 54.44 per cent, owing to the removal of the silica as quartz and of the potassium carbonate. Kaolin is the chief substance of which clay is produced, clay being commonly a variable mixture of kaolin and impurities, such as quartz-flour, iron oxides etc. We see here the process by which this common substance originates as the result of the weathering of feldspars.

Laterization. — In moist, tropical regions the feldspars are not as a rule changed to clay, which is a hydrous silicate of alumina, but to hydrous oxides, chief among which is the mineral Hydrargillite ($Al_2O_3 \cdot 3\,H_2O$), or to a mixture of oxides, forming bauxite. There is usually much iron oxide liberated, especially if the decaying rock is basic, such as basalt, etc. This iron oxide stains the

[1] This clouding may be due to the development of sericite rather than kaolin.

product a deep red or brown, and may also form iron nodules or concretions. The combined product is called *laterite*. It is a very widespread product of rock decay in tropical regions and has been known to extend to a depth of 300 feet in Brazil. In the process of laterization, the silica is separated out and accumulates in separate areas as quartz (agate or chalcedony).

A comparison of the more important compounds of a fresh igneous rock (dolerite, see p. 107) and its decomposition product, brings out the change and shows the difference between kaolinization and laterization.

Important Compounds	Present in Fresh Rock (Dolerite), England	Present in Kaolinization Product	Present in Fresh Rock (Dolerite), India	Present in Laterization Product
Silica (SiO_2)	49.3%	47.0%	50.4%	0.7%
Aluminum oxide (Al_2O_3)	17.4%	18.5%	22.2%	50.5%
Iron oxide (Fe_2O_3)	2.7%	14.6%	9.9%	23.4%

Corrosive Work of the Atmosphere

This is of little importance, as a rule, in rock destruction, though very marked in the case of snow and ice, where the surfaces are often strongly pitted. The corrosive effect of the atmosphere in this case manifests itself largely by a process of direct evaporation. Entire banks of snow and ice may thus be removed by evaporation without passing through a liquid state. The moisture in the air may also have a corrosive effect upon easily soluble deposits, such as salt and gypsum beds, or even limestones, but in general it would be difficult to distinguish this from the work of rain and other waters upon these rocks. Corrosion by hot gases and steam is not an uncommon process in volcanic districts.

Destructive Work of the Wind

Deflation. — Air in motion, *i.e.* wind, often exerts a powerfully destructive effect upon rocks. This is especially the case where material has previously been loosened by weathering, so that the wind merely picks up the loose material and carries it away. The removal of such material by the wind is called *deflation*, and to it is probably due the most extensive effect of wind erosion. Of course, material previously deposited in a region, either that transported by the wind from elsewhere or that brought by running water or by ice, may also be removed by the wind, and this too is

deflation. Many exposed uplands are thus kept free from loose material, which is removed as fast as weathering produces it. The great elevated plateau of southern Germany, known as the Swabian Alp, is in this manner kept almost bare of soil, so that agricultural activities are strongly interfered with. So-called stony deserts or *Hammadas* are produced by the removal by wind of all fine products of disintegration, leaving only the coarser fragments, which are worn and polished by the corrasive effects which this finer material has as it is swept along by the wind.

Corrasion. — This is the second important mode of wind erosion, and this method has already been compared to the work of the artificial sand blast. By means of the sand swept along by the wind, rock surfaces are polished and grooved, such grooves often being very marked and in parallel alignment upon the surfaces of some rocks, such as limestones.

Wind-worn grooves of this type are found in the limestone plateau of the Libyan desert in northern Africa. They extend in a north-northwest by south-southeast direction, and vary in depth up to a meter. They were cut by the sand-laden winds, which for thousands of years have swept across this surface with little or no variation of direction.

Such wind-channeled surfaces may become of considerable importance to the student of earth history, when he finds them on older rock surfaces which were subsequently covered and buried by material deposited upon them and also consolidated into rock. They become visible, of course, only when the later deposited material is removed again by erosion or by quarrying, and it will then be found that the old wind channels are filled in by this younger rock material, a part of which will commonly remain after the removal of the general covering mass. The presence of this material will show that the grooves or channels are not of recent origin, but were formed before the younger rock material was deposited. Such conditions clearly show that after the formation of the older rock, a period of land succeeded, with strong wind activities such as are found chiefly in deserts, and that therefore this interval of erosion marks a considerable period between the epochs of deposition of the older and of the younger rock. An ancient example has been found in Michigan, where limestone surfaces, of Upper Silurian age, are grooved in this manner and are covered by limestones of Middle Devonian age, which fill these grooves as well. This indicates strong wind activity during the interval between the periods of deposition of these two rocks (the Lower Devonian interval), and some of the old, well-rounded sand grains which were active in the production of these grooves are still found in some of them.

In central Asia, surfaces of argillaceous rock are similarly sculptured, but here the sides of the grooves are often strongly fluted. Such surfaces are called locally *yardangs* (Fig. 338), and they too are recognizable when found along the contact of two older rock series, and tell a similar story.

Good illustrations of the corrasive activities of sand-bearing winds are found in the San Bernardino Pass in southern California, where the telegraph poles along the pass are greatly damaged by

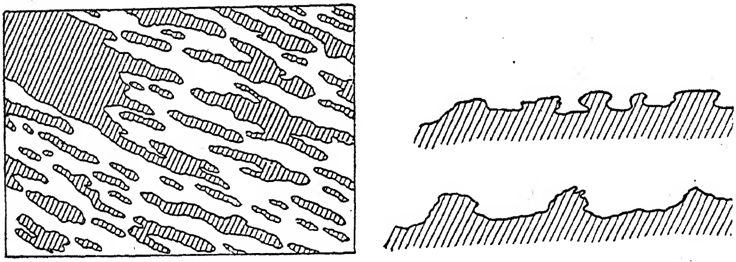


FIG. 338. — Map of a desert area with yardangs, and cross sections of the same on a larger scale. (After Sven Hedin; from Kayser's *Lehrbuch.*)

those blasts, so that they have to be protected by piles of rock and supplemental pieces placed on the windward side. In the Trans-Caspian deserts the telegraph wires stretched along the railroad line were so affected by the sand blasts that they became diminished by half their diameter, and had to be replaced after eleven years. Even the fine dust of the city streets, blown across tombstones in old cemeteries, will in time efface their inscriptions.

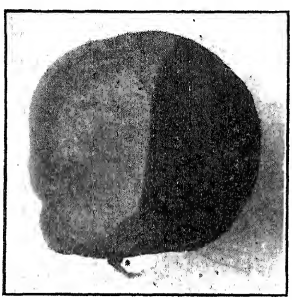


FIG. 339. — Eolian carved pebble — "Einkanter." If the small face on the lower side were enlarged the usual type of "dreikanter" would result. Marthas Vineyard, Mass. Gardner collection of photographs, No. 542. (Courtesy of Geological Department, Harvard University.)

Some of the most striking effects of wind corrasion are seen in pebbles exposed to more or less constant sand-bearing winds, such as are found in desert regions, but also on exposed portions of the coast. Upon such pebbles, smooth, flat faces will be cut, several of these intersecting generally in well-marked angles. Such faceted pebbles or *dreikanter* (so-called because of the usual presence of three edges) are of common occurrence. Sometimes only two facets are cut, these meeting in an edge; then the pebble is called an *einkanter* (Fig. 339).

Abrasion of Sand Grains. — The sand grains carried by the wind are themselves affected by the impact against the rock sur-

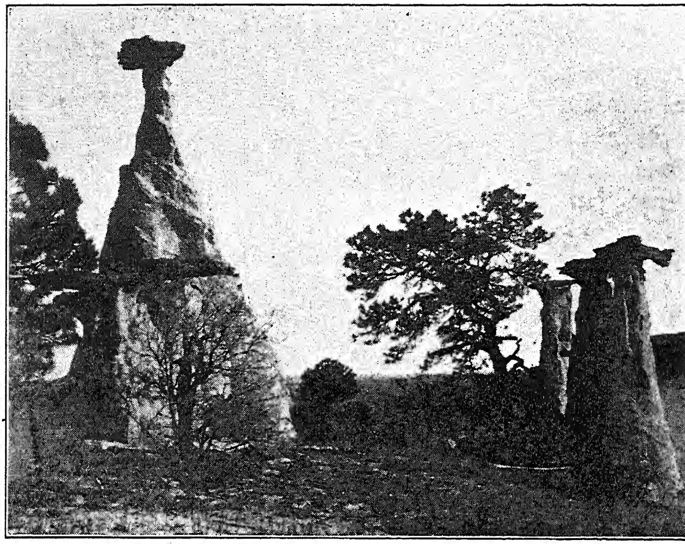


FIG. 340. — Erosion monuments of white sandstone, with harder beds cemented by iron oxide. One of these cuts the large monument near the middle and forms the capstones of the smaller ones. These beds were formerly continuous. Monument Park, Colorado. (Darton, photo; from U. S. G. S.)

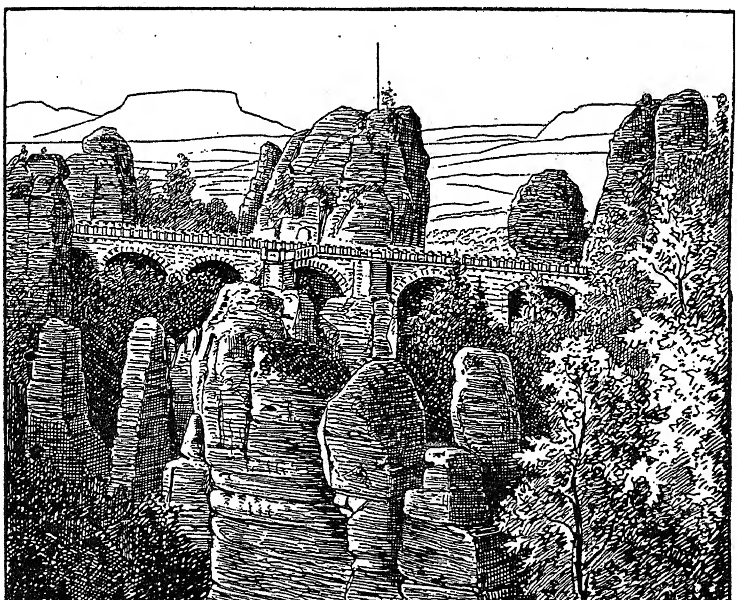


FIG. 341 *a*. — Erosion forms of a jointed sandstone (Quader Sandstein) Bastei, Saxon Switzerland, on Elbe River. (After Kayser, *Lehrbuch*.)

faces as well as against one another. A result of this is, that the grains of softer rocks such as limestones, and those of cleavable minerals, such as feldspar, are often completely ground to dust, which is carried far away, while the grains of the harder minerals, such as quartz, have their angles worn off and their surfaces more or less pitted and given the appearance of ground glass. Grains which have been repeatedly worn in this way may in

FIG. 341 *b*. — Erosion pillars (Three-finger tower) in sandstone, due to weathering and deflation along joint cracks in the rock. Note the size of the men for comparison. Bastei, on the River Elbe, Saxony.

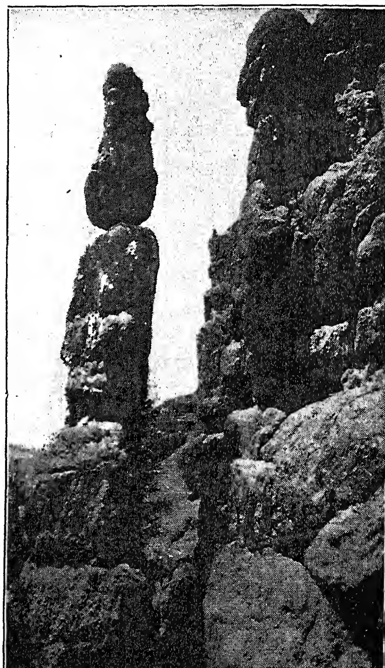


FIG. 342 *a*. — Erosion forms in jointed sandstone, Cedar Breaks, Utah. (Photo by F. J. Pack.)

time approach a perfectly spherical form (millet-seed sands), by which, as well as by other characters, their origin as wind-blown sands can be recognized. Sand grains are, however, rounded in other ways, though on the whole less perfectly. (See Figs. 361 *a*, *b*, p. 440, 370 *a*, *b*, p. 452.)

Combined Deflation and Corrasion. — Where materials are loosened by alternate heat and cold, they can be removed from the exposed surface by wind and at the same time act as tools for the

corrasion of the rock. By such means extensive masses of rock are removed in the course of time, and the material carried elsewhere, where it is redeposited.

Rock masses are commonly cut by crevices, which are called joints, and which penetrate them in all directions. Wind erosion is most active in these crevices, widening and enlarging them. In this manner, pillars of rock may become separated from the original mass, and these pillars may be carved by the wind into fantastic shapes; for the weaker portions of the rock will be cut away more rapidly, leaving the harder portions in relief (Fig. 342 *b*). Exceptionally fine examples of such pillars are found in Monument Park, Colorado (Fig. 340), in the famous Bastei region along the river Elbe in Saxony (Figs. 341 *a*, *b*), in the semiarid regions of the west (Figs. 342 *a*, *b*), in Egypt, and elsewhere. Sometimes only isolated tables or buttes

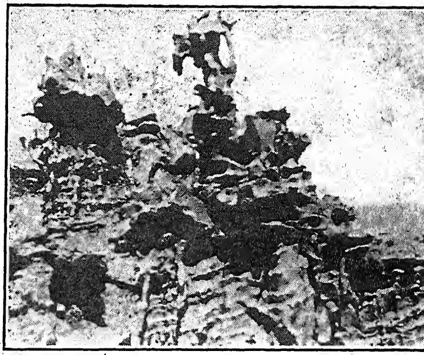


FIG. 342 *b*.—Weird sculpturing by the wind in Tertiary rocks of the Uinta Bad Lands, north of White River, Utah. The harder portions have been etched in relief. (American Museum Natural History.)

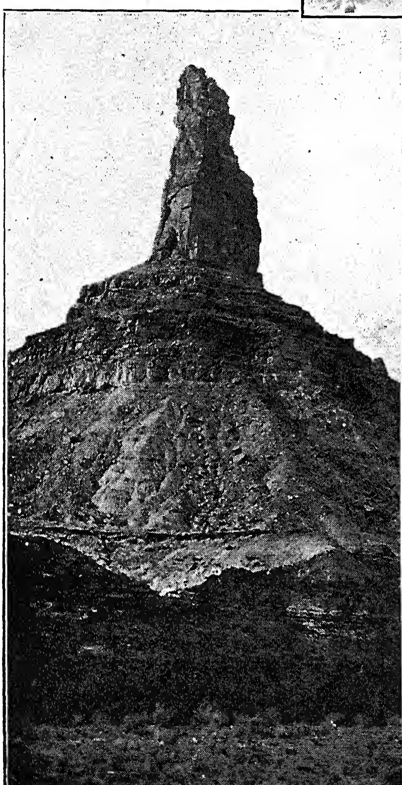


FIG. 343.—Erosion monument, Utah. The spire rises 2000 feet above the base in the foreground. (Photo by F. J. Pack.)

of rock will arise from an otherwise flat surface (Figs. 343, 344) and represent the last remnant of a formerly continuous layer which has been almost completely removed by wind work.

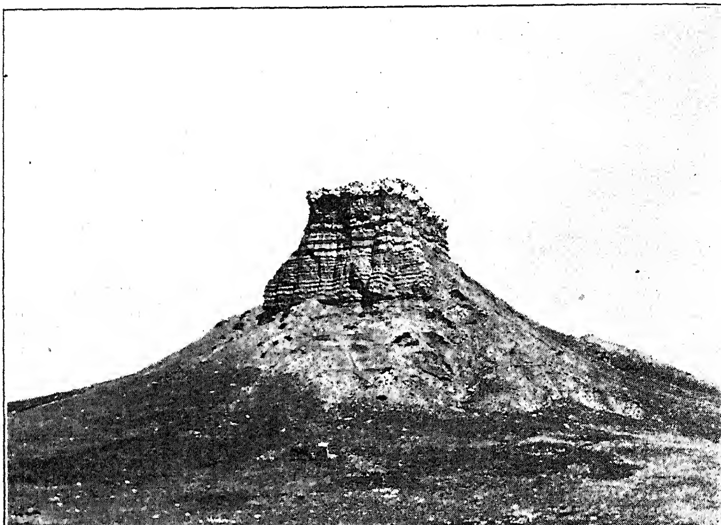


FIG. 344. — A butte of horizontal red sandstone capped by white gypsum, and surrounded by talus slopes. The strata once extended widely over the region. Northeast of Cambria, Wyoming. (Photo by Darten, U. S. G. S. Courtesy of D. W. Johnson.)

DESTRUCTIVE WORK OF THE HYDROSPHERE

Rain-Water

Erosive Work of Rain. — Falling rain forms, in a measure, a transition from the atmosphere to the hydrosphere, originating in the former and becoming a part of the latter as it reaches the earth's surface. Rain erosion is, on the whole, confined to soft rocks, such as salt beds, and to unconsolidated clays and sands, from which it carves pillars, buttresses, and other erosion forms (Figs. 345 *a*, *b*). Its effect is partly mechanical, through impact, followed up by the rivulets into which the rain-water unites, and partly chemical, effecting solution or corrosion on salt, gypsum, and limestone beds (Figs. 346 *a*, *b*). Cold rain-water falling upon highly heated rocks will greatly aid in shattering them.

Disposition of Rain-water. — The water which falls upon the earth as rain is disposed of in three ways. A part of it again evaporates, this being most pronounced where there is much vegetation to retain it for a time. A second part runs off, following the slope of the land. This is most abundant in regions of little or no vegetation, on surfaces composed of hard, impervious material, and on steep slopes. This *run-off* marks the beginning of river formation. A third part finally sinks into the ground, and becomes the *ground-water*. This is most abundant where the surface is composed of loose, porous material, and where its flatness prevents much run-off.

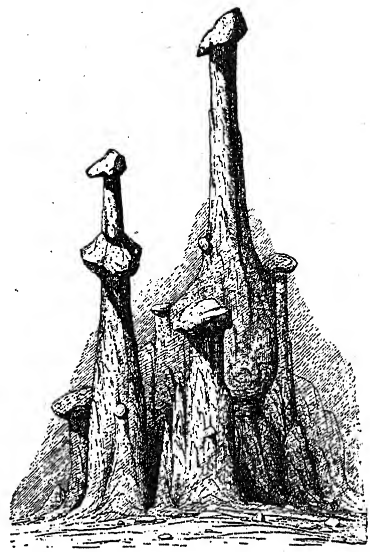


FIG. 345 *a*. — Earth pillars protected by a cap of rock and due to rain erosion, Colorado. (After Hayden.)

Rivers and the Products of Their Erosion

Origin of Rivers. — As we have seen, the run-off of the surface waters follows the slope of the land. At first, if the slope is a homogeneous one, a sheet-flood may result, *i.e.* a broad, shallow sheet of water, without definite boundaries, runs down the slope. Soon, however, because the water washes away loose material, some portion of the surface will be excavated somewhat more deeply than others, and more water will be concentrated in this deeper portion. This leads to increased removal of the loose material along that line, and a gully is formed, which is gradually deepened and widened into a stream bed. At first it is a dry gully, carrying only the run-off after rains. But as soon as the gully is deepened sufficiently to tap the surface of the ground-water, springs are formed along its sides, and a more or less permanent stream comes into existence. In arid regions where the surface of the ground-water lies deep, large valleys or *arroyos* (called *wadis* in Africa) may be

cut by the run-off without reaching the ground-water level. These arroyos will therefore carry water only in rainy periods, being dry for the remainder of the season.

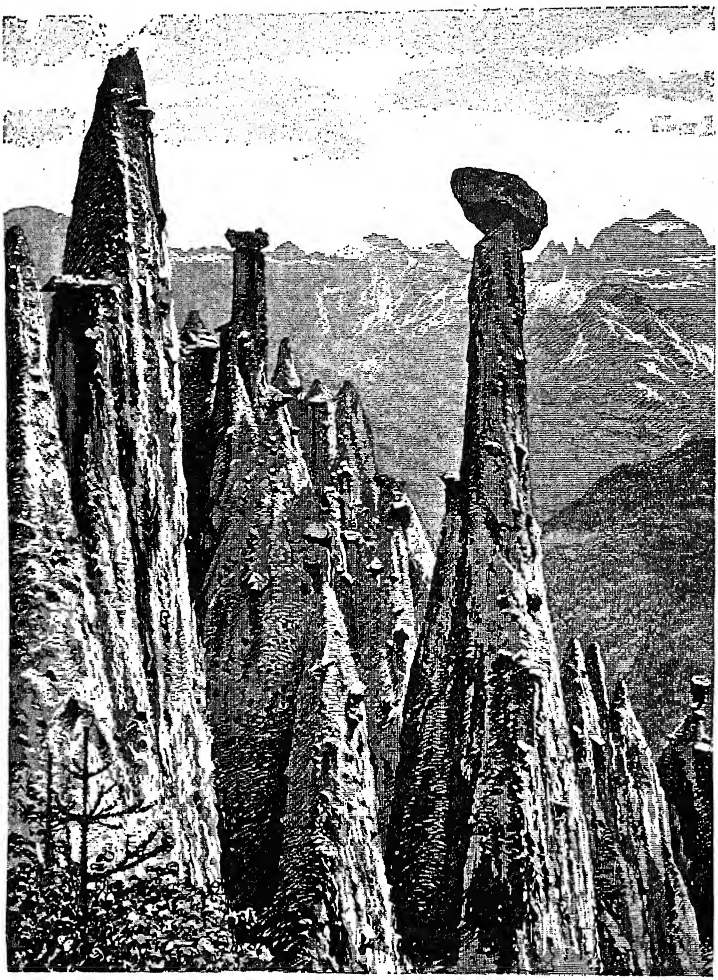


FIG. 345 *b.* — Earth pillars at Bozen, in the Tyrol, due to rain erosion of glacial till. The larger rocks often form protecting caps of the pillars. (After Walther.)

Erosive Work of River-water. — The erosive power of river water varies as the square of the velocity of that water. This will be appreciated when it is realized that if the speed of the river

is doubled, it will, in the same time period, hurl twice as many sand-grains as before, against an exposed rock surface in its bed; but it will also throw each grain with twice the force of its former

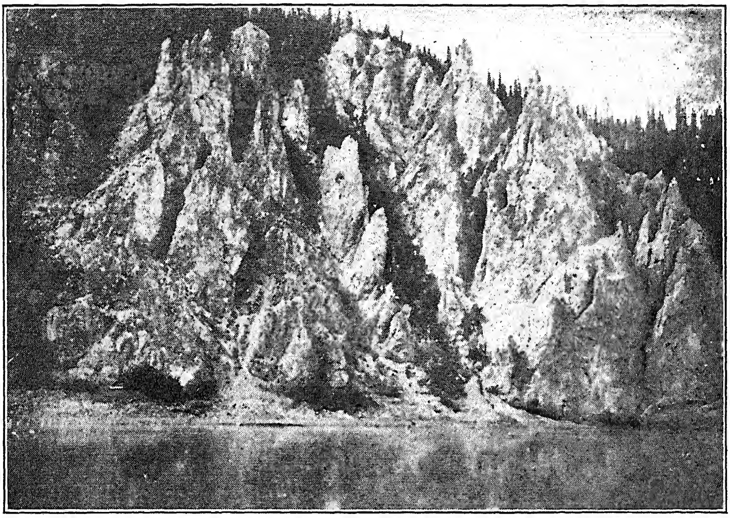


FIG. 346 *a*. — Typical exposure of limestone showing peculiar weathering forms due to solution. (Photo by Collier, U. S. G. S. Courtesy D. W. Johnson.)

speed. Thus the rock-surface will be eroded four times as fast as before the doubling of the speed. The velocity of the water is determined partly by the slope of the river bed, and partly by the volume of the water passing a given point within a given time.

FIG. 346 *b*. — Characteristic surface features on the Sentis in Switzerland produced by solution on exposed limestone surfaces. These are called *lapiaz* or *rascles* by the French and *karren* by the Germans. (After A. Heim.)

Thus in steeper portions of a river-bed, a greater velocity exists and hence more erosion is accomplished. Again, if the volume of river-water is increased after a rainfall, its velocity and erosive power are increased.

The erosive work of river-water comprises *denudation*, or the removal of loose material produced by weathering, etc.; *corrasion*, or the actual scraping or rubbing-off of material from the rock over which it flows; *abrasion* of the pebbles and sand grains which it moves along; *quarrying* by undermining of the banks or at waterfalls and the subsequent breaking down of the undermined rock, and chemical *corrosion* or solution.

Denudation is chiefly confined to the early stages of the river when the water first runs off on the surface of the mantle rock, and by removing part of this, produces its gully. In mature rivers, too, the weathering of the banks provides material which the river removes, and so do lateral branches, which deposit their own débris upon the floor of the main valley, whence the main stream must remove it by denudation.

Corrasion, or the mechanical wearing away of the rock of the river bottom and sides, is perhaps the most important erosive activity of streams. This is accomplished by the tools which the river-water carries along, these tools being the sand or pebbles obtained by denudation or by corrasion farther up stream. If the sand and fragments carried along by the river are largely quartz or a similar hard mineral, while the bed and banks are composed of softer rock, the erosive effects will be most marked in the latter, though the fragments themselves will be gradually worn to rounded pebbles, and the quartz grains will likewise be rounded. This wearing of the pebbles and sand is called *abrasion*.

Abrasion is also accomplished by mutual attrition, or the impact of fragment upon fragment, as they are moved along by the water. If the loose material is of soft rock, it will be rapidly destroyed by such abrasive activities, and the average size of the material will become smaller as we proceed downstream. This is well illustrated by observations made on the river Mur in Austria, where at the city of Graz the average size of the rock fragments in the stream was 224 cubic centimeters. Farther downstream the average size diminished at the following rates, there being here no new material supplied along the course:

At Graz,	224 cc.	56 km. below Graz,	81 cc.
10 km. below Graz,	184 cc.	71 km. below Graz,	60 cc.
26 km. below Graz,	132 cc.	83 km. below Graz,	50 cc.
43 km. below Graz,	117 cc.	101 km. below Graz,	33 cc.

120 km. below Graz (at Unter Manthdorf), 21 cc.

The average distance necessary for rock fragments of different hardness and consistency to be carried by rivers before they become completely destroyed has been determined for some rocks to be as follows:

Sandstone (Rhætic formation) av. wt. 40 grams,	15 km
Clay-slate, av. wt. 24 gr.	42 km
Compact limestone (Ordovician Orthoceras limestone) av. wt. 61 gr.	64 km.
Granular limestone, av. wt. 40 gr.,	85 km.
Granite, av. wt. 36 gr.,	278 km.

The vast superiority of resistance of granite over that of the other rocks is at once apparent. A similar differential destruction of the minerals derived from the disintegration of rocks is effected by the abrasive process. As an example may be cited the sands of some Scottish rivers (Eastern Moray) which are derived from the destruction of the fundamental gneiss. In the river Spey, the percentage of feldspar at one point (Cromdale) was 18 and of mica 1, while farther down-stream (at Orton), the feldspar made up only 12 per cent of the sand. In the river Findhorn, near and parallel to the Spey, 42 per cent of feldspar was found in the sand at one point (above Dulsie Bridge), while lower down (between Forres Bridge and the sea) the percentage was reduced to 21. This more rapid destruction of the feldspar is in large part due to the ready cleavability of this mineral. The fine particles resulting from this destruction are carried away by the current.

Sand grains carried by river-water are rounded by mutual attrition and by contact with larger rock masses. The problem is a complex one, but in general it may be said that the rounding is less effective than in the case of wind-blown sand. Moreover, it is generally true that the smaller grains will be less well rounded than the larger, and very small grains may not be rounded at all (except by solution), while grains of the same size will readily be rounded by abrasion in air. This is one of the means by which river sand may be distinguished from wind-blown sand, but it must be used with caution because of the many modifying factors.[1]

Quarrying, by undermining the banks, is an effective way of widening the river valley and of supplying new material for pebbles and sand. In river gorges the bank on the outer or convex side of the current is commonly kept vertical or overhanging by this undermining process, because the principal current of the river always makes more pronounced curves than the river as a whole, and so flows close to the foot of the concave bank on the convex side of the river, as illustrated in the following diagram (Fig. 347 *a*). On the

[1] For a fuller discussion see Grabau, *Principles of Stratigraphy*, pp. 253–257, with literature references, and a recent paper by J. J. Galloway, which attacks the problem from the experimental point of view (*Am. Journal of Science*, vol. xlvii, pp. 270–280).

concave side of the river (convex bank) a talus slope is generally formed from the accumulation of the products of weathering (Fig. 347 *b*).

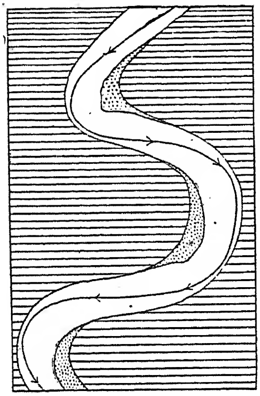


FIG. 347 *a*. — Diagram showing the stronger meandering of the current as compared with the river as a whole.

The manner in which a stream changes from a straight to a winding or meandering course may be briefly set forth.

In a straight channel of uniform cross-section, occupied by running water, the greatest velocity of current is found in the center and, with still air, just below the surface of the water. This is readily shown by experiments with floats in mill-races, or other artificial canals. The reason for this is the fact that the center of the stream is free from friction which affects the sides and bottom of the stream, while the surface film of water is affected, though to a much less degree, by friction against the atmosphere. If an obstruction is placed in a channel on one side, the main velocity current is at once deflected away from this obstruction and obliquely towards the opposite side, against which it may impinge, and from which it may in turn be again deflected. This time the deflection will be in the opposite direction, and the current will again cross the channel obliquely in its downstream course. Thus a single obstruction may throw the main current into a zigzag or winding course, which causes it to impinge alternately against the right and left banks in its onward flow.[1] When the current strikes the bank it will remove loose material by its impact, this being especially marked, where the banks consist of unconsolidated material. When the current rolls and sweeps along pebbles and sand, these will be hurled against the bank at the point of impingement, and such river tools will perform their chief corrasive work at this place. Thus the banks become indented alternately on

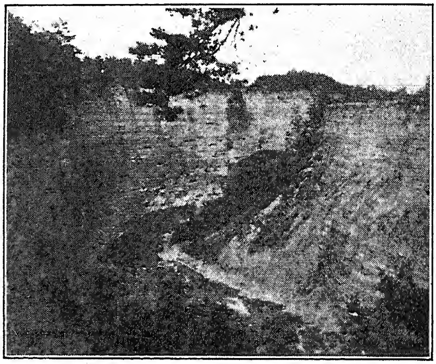


FIG. 347 *b*. — Gorge of the Genesee River below Portage, showing the vertical bank (260 feet high) on the outer or convex curve of the river (concave bank) and the talus-covered slope on the opposite side. (Photo by author.)

[1] The right and left bank of a stream are those on our right and left hand, respectively, when we face downstream.

opposite sides, and this causes a further increase in the deviation of the current from the original straight line. Meanwhile a part or the whole of the material removed from the bank at the point of impingement is dropped again in the slacker water below the point of erosion, or in general opposite the point where the current next strikes the bank. Thus erosion and deposition alternate on the same side. As the result of the building of a new sandbank on one side, and the indentation of the old bank on the opposite side, the stream itself will

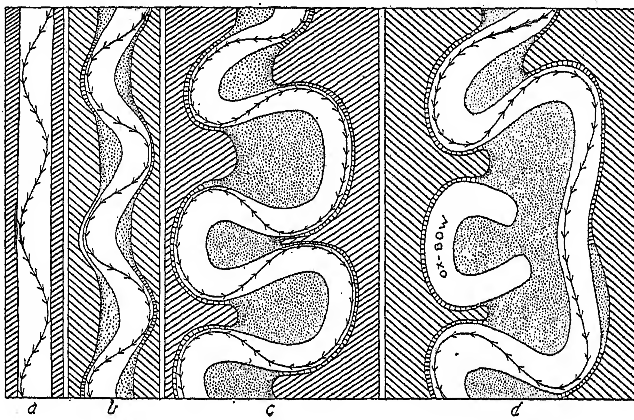


FIG. 348. — Diagram illustrating the development of meanders in a river. *a*, a straight channel, the main current has been deflected by an obstruction above, and has assumed a winding course; *b*, the entire river has begun to meander by cutting into the banks at one place and building sandbanks on the same side next below; *c*, extreme meandering course, two of the meanders nearly touch, and the formation of an oxbow on the left is imminent; *d*, completion of the oxbow or cut-off.

assume a winding course, as shown in diagram *b*, Fig. 348. The continuation of this process will result in changing the original straight form of the river into a series of curves or meanders, as they are called, from the river Meander (now called Mendere) which flows into the Ægean Sea near Miletus (Palatia) in Asia Minor and in which such curves are very pronounced (Fig. 348 *c*. See also Fig. 604). The continuation of this process may result in the cutting off of a very pronounced meander which then remains behind as an "oxbow" frequently forming a crescentic lake (Fig. 348, diagram *d*. See also Fig. 605).

Undermining is also carried on actively at the foot of a waterfall, where the spray from the falling water attacks the cliff behind it. This is the origin of the Cave of the Winds at Niagara, where a hard limestone forms the top of the fall and a softer shale, or mud-rock, the lower part. This softer rock is worn away by the spray, both by the impact and by freezing, while the harder limestone projects.

At intervals this overhanging mass breaks down, and large blocks of limestone accumulate at the foot of the cliff (Fig. 349). The several recorded falls of Table Rock are illustrations of such sudden changes after a long period of undermining. Waterfalls also perform effective erosion upon the river-bottom at their base, especially if the volume of water is great. This impact of the water and the grinding work of the rock fragments, which it sets in motion,

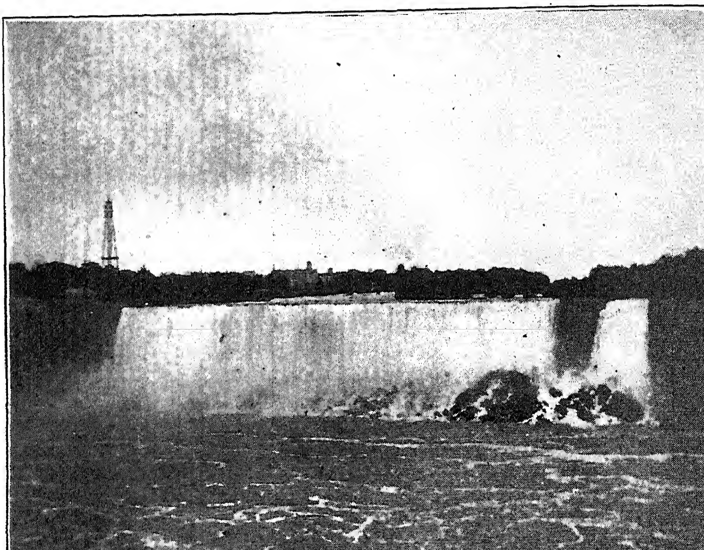


Fig. 349. — The American Falls at Niagara, as seen from the Canadian side; showing the numerous blocks of limestone which have fallen from the edge of the cliff, because the soft shale beneath them has been eroded by the spray. The force of the water is insufficient to destroy these rocks or to use them in eroding the bottom as is the case at the Horseshoe Falls. (Photo by author. See also Figs. 666–669.)

result in deep excavation of the bottom. The "swimming hole" at the foot of a small waterfall is a familiar example. The Horseshoe Falls at Niagara have excavated the river-bottom to a depth of 150 to 200 feet, or more than the height of the falls above the river-level at their base. As these falls have been slowly receding for a long time, the gorge has been deepened to this extent throughout a distance of over three miles by this process. (See further, Chapter XXIII.)

There are many special erosion features of rivers, which will be discussed under the sculpturing of the earth's surface. Of these,

pot-holes may be mentioned in this connection (Fig. 350 *a*). These are local excavations in the river bed, formed wherever an eddy is

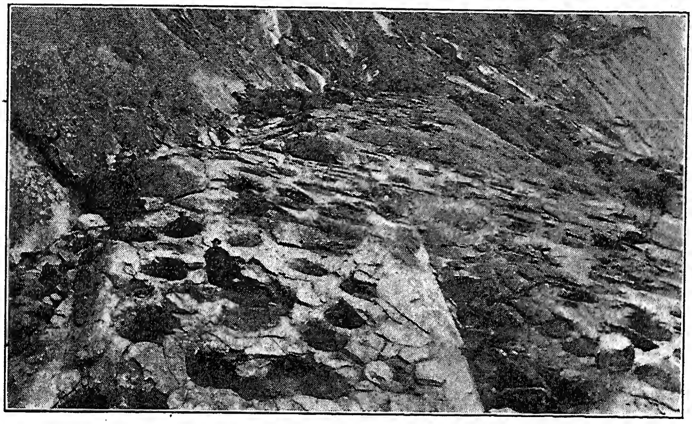


Fig. 350 *a*. — Pot-holes at Harris Salt Springs, worn in granitic rock by eddies in the bed of a stream, Tuolumne River, Cal. (Photo by Turner, from U. S. G. S.)

produced which sets up a whirling motion of the sand and pebbles. The holes cut by this whirling motion are round in section and have

Fig. 350 *b*. — Pot-holes above the present level of the stream that formed them. (After Geikie.)

vertical sides. They may vary up to 20 feet or more in diameter, and may be of equal or greater depth. They are most frequently

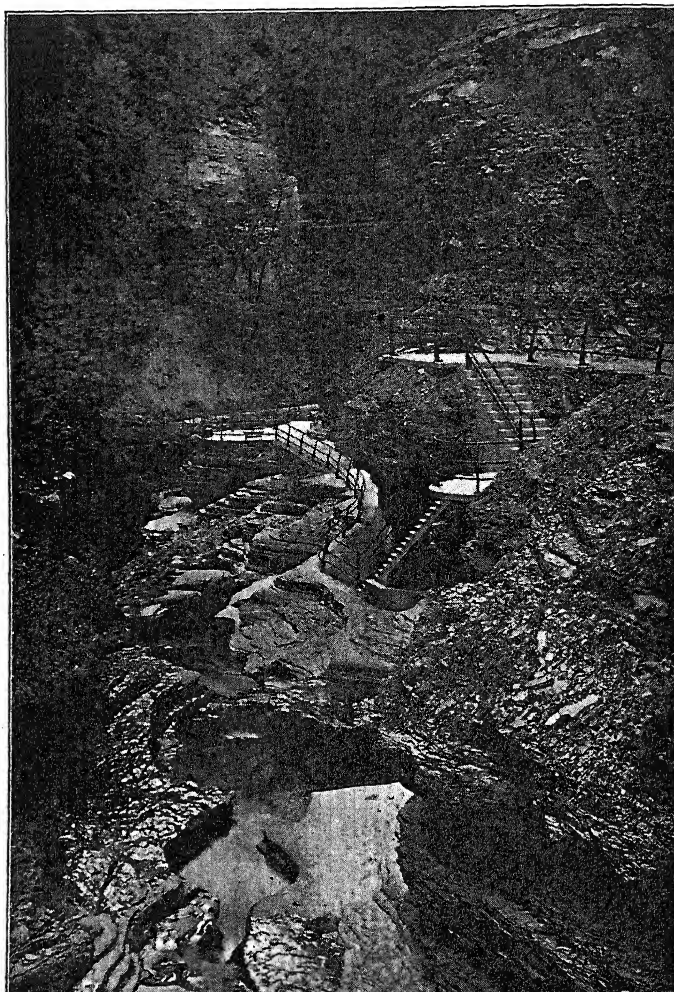


Fig. 351. — Watkins Glen, N. Y., a narrow gorge largely formed of confluent pot-holes, cut in shaly sandstones of upper Devonian age.

found in the beds of mountain torrents and near waterfalls (Fig. 350 *b*). A series of confluent pot-holes of large size may produce

a deep and narrow gorge, as is the case in Watkins Glen in southern New York (Figs. 351, 352).

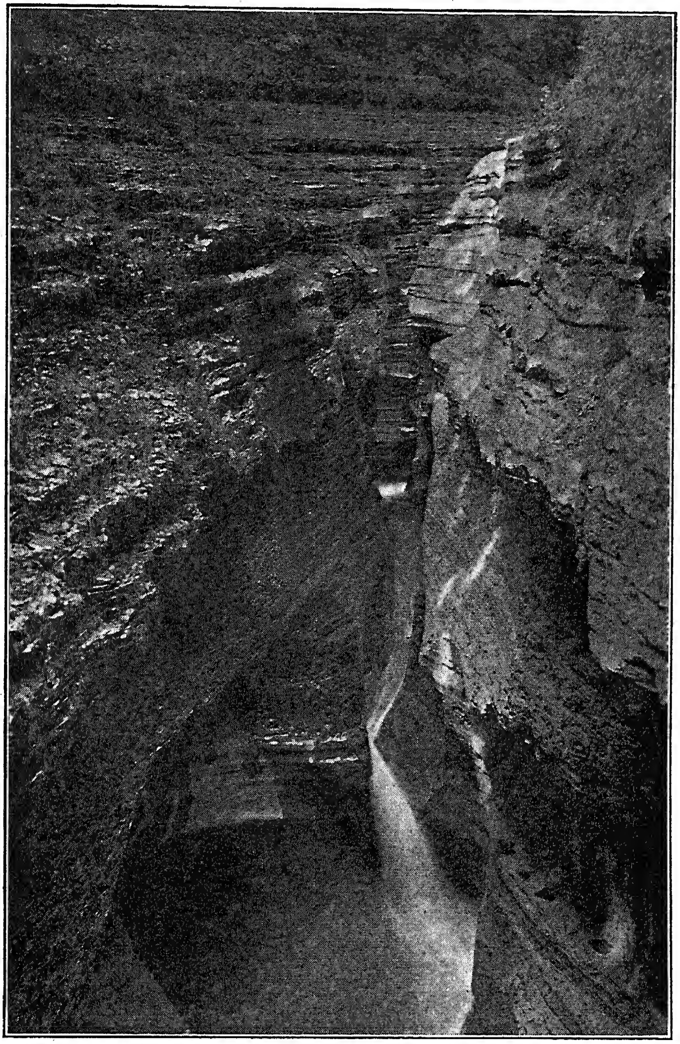


FIG. 352. — One of the larger pot-holes in Watkins Glen, N. Y.

Corrosion. — Solution or chemical corrosion is on the whole of little importance in rivers, though it is accomplished wherever limestones or other soluble rocks are encountered. Most of the material held by river-water in solution is, however, furnished to it

by the underground water which issues as springs along the river border.

Underground Water

Types of Underground Water. — The water which sinks into the ground forms a part of the underground or subsurface water. The quantity of such water depends on the climate, the porosity of the rock or soil, the surface slope of the land, and other factors. As the water sinks into the ground, it reaches a level at which its further progress through the rock and soil becomes so slow that it may be regarded as stationary. This forms the zone of saturation, and the water there forms the true ground-water. The upper level of this zone is called the *water-table* or ground-water level, and it varies in depth in the same locality with the season, and for longer periods, with the character of the rock, the amount of rainfall, etc., and in different localities with the climate etc. (p. 441). It is not a level surface, but varies with the contour of the land and other factors. It is this lowest average level of the water-table which must be reached by wells to be permanently supplied by unfailing springs.

The spaces in which this ground-water flows are partly large fissures and partly minute interstices between the grains. These interstices vary with the character of the rock and to some extent with its age. The larger openings also vary with the character of the rock and the disturbances to which it has been subjected. They comprise the planes of bedding between sedimentary rocks, the joints and other fissures which traverse it, solution cavities, etc. In the larger fissures the ground-water is chiefly controlled by gravitation, but in the smaller interstices within the rock the water is subject to the force of *adhesion,* which is the mutual attraction of rock and water, in minute quantities. This force of adhesion is most pronounced in rocks with the smallest interstices. When the interstices are so fine that their walls will attract all the water they can hold, or if interstices are few and far between or are absent altogether, the rock is called *impervious* to water under ordinary conditions, that is, it will not permit water to pass through it. This of course implies that no cracks or fissures of subsequent origin are present. Other rocks are more or less *pervious* or permeable to ground-water under ordinary conditions, the degree of permeability depending on the porosity of the rock and on the amount of fissuring which it has suffered.

That solid appearing rocks also will take up water can easily be shown by immersing them in water, and noting the difference in weight between the dry and water-soaked rock. The water occupies the spaces between the rock particles. Such spaces may constitute as much as thirty per cent or over (in some cases 60 per cent) of the volume of the rock, or they may form less

than one per cent of its volume. The greatest porosity is found in rocks composed of grains of uniform size and spherical form, especially if the arrangement of the grains is such that they rest vertically one upon the other. Rocks made up of rounded and uniform grains are best produced from wind-blown sands, and hence, where such rocks are part of the bedded rock series of the earth's crust, they form good media for the transmission and storage of underground water, provided the changes in character and position which they have undergone are not unfavorable to such processes. Unconsolidated sands and pebble beds are of course among the best of media for the transmission and storage of underground water, but if these are surface deposits, they do not afford good reservoirs for well waters, since they also admit the surface drainage.

The rate of flow of underground water varies greatly, being especially influenced by the porosity of the rock. Though locally it may be relatively rapid, the average rate of flow is probably not much over a mile a year.

As stated above, the name *ground-water* is applied to the water in the zone of saturation, that is, the water below the water-table. This water is also called *phreatic water*, a term derived from the Greek word for *well*, because it is the water which supplies wells and springs. The water in the rock and soil above the water-table, held there temporarily by molecular attraction against gravity, but slowly sinking to the level of the water-table, constitutes a part of the *vadose* water, which is the name applied to all the subsurface water circulating through the soil or rocks above the water-table.

The best conditions for the storage of well-water are found when a horizontal or gently inclined pervious bed is covered by an impervious one, for this will keep out the surface drainage. It is of course necessary that all wells sunk through such an impervious bed should be properly protected above the level of that bed, to prevent the entrance of surface waters. The entrance of the water into the pervious bed takes place at its outcrop, which may be many miles removed from the region where the water is tapped.

The surface of the ground-water or the water-table is not a level one. It rises inland from the sea, and conforms somewhat to the irregularities of the country, but is much less diversified. The porosity of the rock, the amount of rainfall in the region, the presence or absence of much vegetation, especially forests, etc., are among the factors which influence the position of the water-table in a given region.

Where valleys are cut below the surface of the ground-water level, this water will issue along their sides in the form of *hillside springs*. Where the ground-water level and that of the surface of the land coincide, swamps are produced; where the land-surface is depressed below the normal water-level, lakes are formed.

Where porous or permeable layers enclosed by impervious ones crop out along the mountain sides or at a considerable elevation, the water entering them will gradually find its way to lower levels, but because of the elevation

of the point of entrance, the water thus stored in the porous rock will be under great hydrostatic pressure. If now wells are sunk in the low country to this porous rock, the water will rise, because of the pressure it is under, and overflow at the surface, or if the country in which the well is sunk is much lower than the head of water at the intake, a gushing well may result. Such wells are called *artesian wells*. Their relationship to the intake near the mountains is shown in the diagram (Fig. 353). If the rock of the low country is intersected by dislocation-planes or faults (see Chapter XIX), the water may rise along such planes and form *artesian springs*.

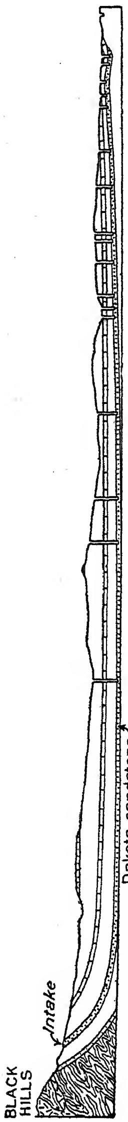


FIG. 353. — East-west section across South Dakota to show the Dakota artesian system. (From *Military Geology*.) The Dakota sandstone is composed for the most part of well-rounded and well-assorted quartz grains, representing an ancient river and wind-formed sand deposit. It is covered by impervious beds of shale and limestone and is steeply uptilted on the flanks of the mountains, so that its outcrop is at a considerable elevation. The nature of the rock, its position, and relation to enclosing rocks, present all the requisites for artesian conditions, and numerous artesian wells have been drilled down to it in the plains country.

Beside the two types of subsurface waters mentioned, there are two others to which reference has already been made in previous chapters. These are the *connate* waters, or the waters originally included in the sediments deposited in water, either salt or fresh, and the *magmatic* or *juvenile* waters, which are formed as emanations from deep-lying igneous magmas. These are, however, of little inportance in rock destruction.

Destructive Work of Underground Water. — The only kind of destructive work which underground water performs is chemical, comprising solution and hydration, and indirectly, oxidation and carbonation by carrying oxygen and carbon dioxide. Oxidation, hydration and carbonation have already been described.

Solution. — This is most effective in limestone regions, where caverns are dissolved out by the circulating ground-water above the water-table, *i.e.* within the vadose belt. Solution of limestones is accomplished by the aid of carbon dioxide which the water carries, and in the resulting solution, an extra mole-

cule of that gas is locked up for each molecule of calcium carbonate. On the re-deposition of the calcium carbonate, this extra molecule of CO_2 is again liberated. Caverns are most readily dissolved out along the bedding planes of the limestone and along the cracks or joints which intersect it. After the cavern has been dissolved out it is slowly filled up again by stalactite and stalagmite growths, though this may go on in one part of a cavern while solution enlarges another. If the water-table rises so that the ground-water will drown the cave, its walls may become lined with crystals of calcite, often of enormous size, or with other

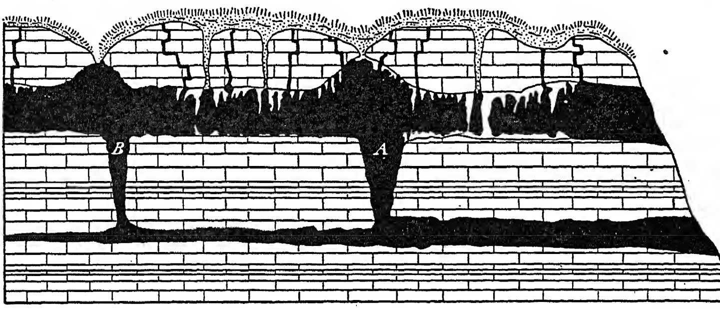


Fig. 354. — Diagram of a cavern, showing different levels of the underground stream. (After G. C. Matson, U. S. G. S.) *AB*, Connecting funnels between the upper and lower cavern. The latter is undergoing active solution, the ground-water level having been lowered to it, while deposition of stalactites and stalagmites goes on in the upper level, where pillars have also been formed. A sink hole is seen on the left of the diagram, and several others filled with soil are indicated. (See also Figs. 184 and 185, pp. 263, 264.)

deposits (copper salts, etc.). The crystal caves of Missouri are examples. The characteristic deposits in limestone caves have already been discussed (pp. 262–265).

On the surface of the country where caves abound there are commonly found more or less circular depressions called sink-holes or swallow-holes (Fig. 354), which form entrances for the waters to the cave and were dissolved by the waters thus entering the underground drainage. Other irregular hollows are formed by the breaking or incaving of the roof of the cavern. The Natural Bridge of Virginia (Fig. 355) is the last remnant of a cavern roof.

Other rocks besides limestones are subject to solution by the subsurface waters. Among these rock salt and gypsum are the most conspicuous. Even quartz is dissolved, especially when the sub-

surface waters contain much humic acid from plant decay, and it is indeed this dissolved silica, which is carried by the streams into

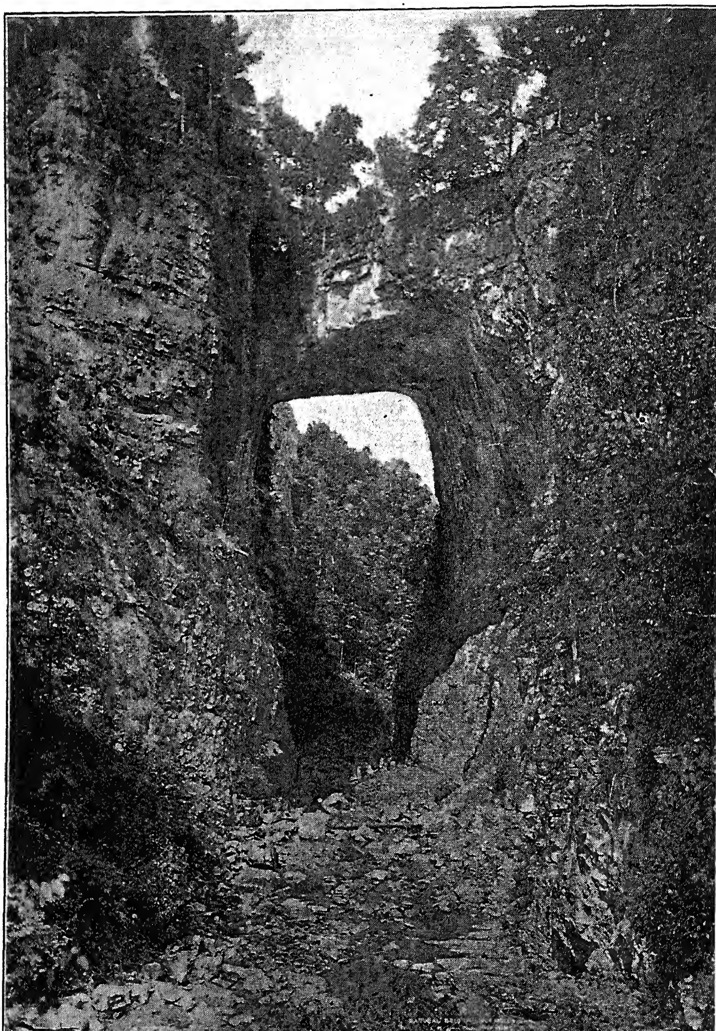


FIG. 355. — Natural Bridge, Virginia. A remnant of a former cave roof. The rock is lower Ordovician limestone. (Courtesy of D. W. Johnson.)

the sea, that constantly supplies the material from which the radiolarians and the diatoms construct their silicious cases.

The rate of solution varies greatly, and is strongly influenced by

the temperature of the ground-water. When this temperature approaches the freezing point, the solvent action of the water is practically lost. The warm springs of Bath, England, with a mean temperature of 120° F., discharge annually a quantity of dissolved sulphates of calcium and sodium, and chlorides of sodium and magnesium, sufficient to make a square column of mineral matter nine feet in diameter and 140 feet high. The great deposits of lithographic limestone at Solnhofen in Bavaria are reduced by solution one meter in thickness in every 72,000 years, and the similar extensive limestones of the Nittany Valley in Pennsylvania, one meter in every 30,000 years. The materials removed by solution each year throughout the entire globe have been estimated at 96 tons per square mile, of which calcium carbonate constitutes 50 tons, calcium sulphate 20 tons, sodium chloride 8 tons, silica 7 tons, alkaline carbonate and sulphates 6 tons, and oxide of iron 1 ton (T. Mellard Reade), leaving 4 tons for other substances.

Indirect Formation of Clastic Rock Due to Underground Solution. — When the roof of a cave breaks down, the rock comprising it is broken into large and small angular fragments, which are piled together in a confused heap. Such breaking down of the surface rock is frequently seen in limestone regions, and is even more marked where gypsum and salt have been extracted. Thus in many regions of western England, where the salt (Permian) is mined by the solution process, extensive cavings have occurred, often destroying villages and parts of small towns. Because of the angularity of the material resulting from such a break, it has a distinctive character, and the name *brecciation* is applied to the process, and *brecciated material* to the result. When reconsolidated it becomes a brecciated rock, or, for short, a *breccia*. Such cavern breccias are not uncommon among the rocks of the earth's crust. Other breccias, such as fault breccias, volcanic breccias, etc., have already been referred to. (See further Chapter XVIII.)

Destructive Work of the Waves

The waves of the sea and of lakes exert a powerfully destructive effect upon the margins of the land on which they border. This destructive effect is due in part to the mere impact and lifting power of the water and its prying power where it enters crevices, and in part it is due to the work of tools which, in the form of sand and

rock fragments, are hurled by the waves against the cliff, or moved along over a rock surface.

The force of the waves in great storms is often very surprising. Measurements on the north Scottish coast have shown the force of impact to be 611 pounds per square foot in summer and 2086 pounds per square foot in winter, while exceptional storms may produce an impact of waves nearly three times that amount. The greatest recorded pressure was 6083 pounds per square foot during a heavy westerly gale near the end of March, 1845. Measurements recorded from the French, Italian, and north African coasts show ranges from 600 to more than 3000 pounds per square foot. As an illustration of the power of the waves to lift rock material may be cited the breakwater in the harbor of Wick on the northeast coast of Scotland. This breakwater consisted, above the foundation, of three large blocks, weighing 80 to 100 tons each, across which a huge concrete monolith, weighing over 800 tons, was cast in place and firmly anchored to the blocks by iron chains. The total mass weighed 1350 tons, and yet during the great storm of December, 1872, it was lifted by the waves and hurled into the inner harbor, a distance of 10 to 15 meters, the monolith and three foundation stones remaining anchored together and being moved as a single mass.

The erosive work of waves is confined to ablation processes, and these are chiefly restricted to quarrying and corrasion and abrasive work. There is, in addition, a certain amount of solution going on, as well as prying by the freezing of the spray and the compression of air in crevices, but these are of minor importance.

Wave Quarrying. — By the constant impact of waves against the cliffs, rock fragments are loosened and lifted from their position. This is especially the case where the rock of the cliff is traversed by cracks or fissures. On the Massachusetts coast, the basaltic dikes commonly have a rude columnar structure, the columns extending across the dike from wall to wall. Wave impact loosens these columns, and they are then lifted out by the waves and carried away, and thus the shoreward ends of these dikes are marked by deep parallel-sided chasms (see Fig. 135, p. 192). On the Irish coast, the columns of basalt which form the Giant's Causeway (Fig. 120, p. 176) are similarly removed by the waves, and on the island of Staffa on the Scottish coast, such removal has produced the famous Fingal's Cave (see Fig. 122, p. 178). Other examples are found on the coast of the Bay of Fundy and elsewhere, and such removal of columns produces, usually, a steep or vertical cliff. When granite cliffs dip into water of moderate depth, steep cliffs are seldom produced, especially if the granite shows few fissures or structure planes which permit such quarrying operations. The

waves have comparatively little effect upon granite, which, because of its hardness, is not easily corraded. The upper parts of the cliff, therefore, being subject to the attack of the weather, will retreat more rapidly than the lower, and a sloping granite headland will project into the sea (Fig. 356 *a*). If the granite is fine-grained and is traversed by many joint fissures, the quarrying operations of the waves are of course facilitated.

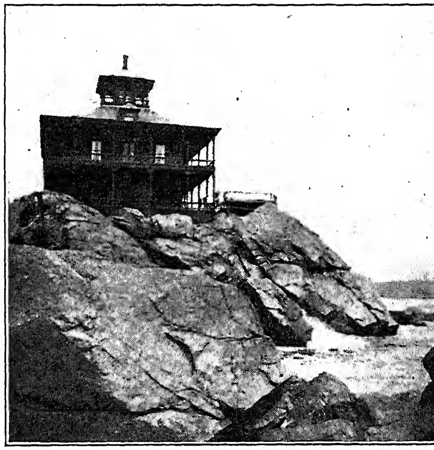


Fig. 356 *a*. — Granite headland, Marblehead, Mass., showing the sloping surface which is due to the more effective attack of the weather on the upper part of the cliff as compared with wave erosion which is effected mainly in the joint fissures. (Photo by author.)

Rocks which are characterized by bedding planes may be quarried into large blocks by waves. Such effects are seen in the limestone and chalk cliffs of the English and French coasts (Fig. 201, p. 279, and Fig. 713), especially upon the North Sea coast of England. Many of the vertical cliffs of softer rocks are, however, produced by corrasion at their base and by the falling of the masses of rock thus undermined.

Corrasion and Abrasion. — When the waves hurl sand and rock fragments against the base of a cliff, this becomes subject to wear by corrasion. The sand and rock fragments at the same time suffer erosion by a process of *abrasion*. Cliffs of soft rock are especially attacked in this manner, and where the wave work is more or less constant at their base, they are apt to present a vertical face (Fig. 16, p. 31). The rate of wear varies, of course, with the force and constancy of the waves and the degree of softness or corradability of the rock, as well as with the hardness of the tools employed by the waves.

The rock fragments employed as tools by the waves, whether broken off by the waves themselves or supplied by the weathering of the cliff, suffer wear. This is most pronounced upon the angles

and corners of the fragments. In this manner angular blocks are rapidly worn into rounded pebbles and boulders (Figs. 356 *b*, *c*). Sand grains suffer in a similar manner, and the softer or more cleavable minerals among them are rapidly destroyed, so that the remaining sand is largely or wholly composed of quartz grains.

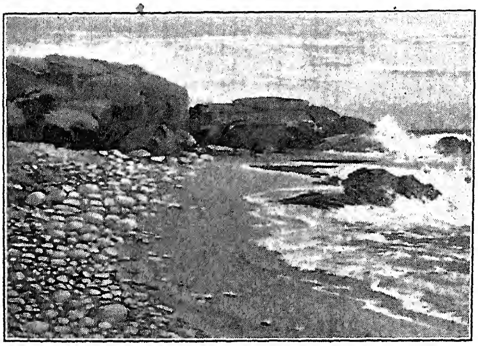


Fig. 356 *b*. — A sand and cobble-stone beach with rock ledges in the background.

On shores characterized neither by rock cliffs nor by glacial material, such as drumlin moraines, etc. (see Fig. 447), pebbles and boulders are relatively uncommon, though some of them may be transported for considerable distances by shore currents. Even where the pebbles are not hurled against a cliff, but are merely rolled back and forth by the waves, mutual impact will effect a

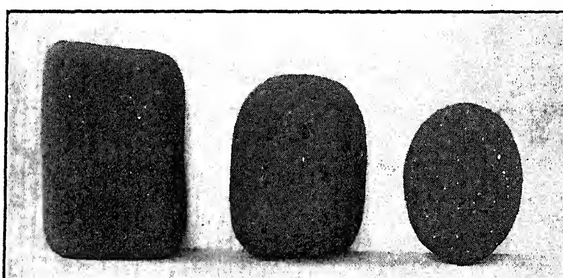


Fig. 356 *c*. — Pebbles worn from bricks by the waves, Nahant, Mass. These fragments illustrate three stages in pebble making. The first is rectangular, with only the corners and edges worn off; the second is sub-rounded and the third fully rounded, though still retaining the elongated form of the original. (F. H. Lahee photo, from Gardner collections of photographs, No. 7401. Courtesy Geol. Dept., Harvard University.)

wearing off of angles and corners, and rounded pebbles result. By continued wear these will be reduced to smaller and smaller size and may eventually be reduced to fine dust or rock-flour.

Sands, which make up most of the material of shores not bounded

by cliffs, also have their grains worn round by mutual abrasion. Such rounding, however, affects primarily the larger grains, which from their size and weight come more constantly in contact with one another; the smaller grains, being more readily held in suspension by the agitated waters, suffer less abrasion and so remain more generally in an angular state. Moreover, the wet sand of a beach commonly forms a compact mass, owing to the water between the grains, so that a gently sloping sand beach is often nearly as hard surfaced as a rock floor. Here the waves have little effect, and the rounding of the grains by mutual abrasion is greatly retarded (Fig. 357).

FIG. 357. — Daytona Beach, Florida. A hard-packed sand beach, extending for many miles. A favorite beach for automobile races.

On the whole, the grains of beach sands may be regarded as much less well rounded than those worn by wind, this being especially true of the smaller grains. Nevertheless, there are many modifying influences, and caution must be used in the employment of this criterion for the determination of the origin of a given mass of sand grains.

DESTRUCTIVE WORK OF THE PYROSPHERE

In volcanic eruptions of the explosive type, both the semi-fluid and the solid lava and the solid rock of non-volcanic origin may be shattered. The size of the fragments thus produced may range from large blocks to the finest dust, the finer material being as a rule more abundant. When lava, which has not yet become thoroughly hardened, is shattered by an explosion during the eruption, these fragmental lava masses are hurled into the air and may harden in the process. The larger blocks will fall back to the

surface in the neighborhood of the volcano, and form rounded, elongated, or otherwise shaped *volcanic bombs* (Fig. 58, p. 116). Such bombs generally show rounded surfaces from the molding process which the mass of lava underwent in its passage through the air, this being often accompanied by a gyrating or spinning movement. When solidified lavas are shattered, large angular fragments are produced, which may form great accumulations and be subsequently bound together to form volcanic agglomerates. Other rocks shattered by these explosions will also produce angular fragments, though of course all such fragments may subsequently be rounded by becoming water-worn. The finer products of shattering of still viscid lavas are known as *lapilli*, and they also show rounded or smooth surface characters. Fine fragments resulting from the shattering of solid rocks, on the other hand, will be sharply angular. The finest volcanic dust is carried into the upper atmosphere and may be transported by the air-currents over wide areas before it settles again. Such material is generally recognized only by microscopic examination, which reveals the fact that it is largely or wholly of volcanic origin. (See Fig. 488.)

Destruction of Rocks by Movements of the Earth's Crust

When through some disturbance in the earth's crust, either volcanic or under the influences of stresses and strains, a fracture arises, movement of the rock masses along such a fracture will result in the grinding and fragmentation of the contiguous rock walls. Such movements may be back and forward, or they may be mainly in one direction, the moving mass producing a displacement of the crust or a *fault* (Figs. 542, 543, Chapter XIX). Such disturbances are commonly manifest on the surface as earthquakes, and may be shown by actual displacements, either horizontally or vertically, of the adjoining masses of rock and of the soil and other structures upon it. (See further, Chapter XXI.) Within the fissure the shattered material from the walls will accumulate, commonly in the form of coarse and fine fragments thoroughly intermingled. The fragments will be angular and will consist of the material of the adjoining walls of the fracture. Such a mixture of angular fragments and fine rock, sand, and rock-flour is called a fault rubble, and when consolidated forms a *fault breccia* (Fig. 32, p. 80). Fault breccias may occur in vertical or inclined fissures, or they may lie in hori-

zontal beds between two masses of rock, one of which has been pushed over or under the other, or both of which may have moved past each other. Its angular character, and the fact that the material consists only of the broken fragments derived from the enclosing rocks, distinguish such a fault breccia from other rubble rocks.

Rock Destruction by Glaciers

Ice is a rock, though only a temporary one in most climates, and the movement over other rock of an ice mass, such as that of a glacier, is analogous to the movement described in the preceding section. One may of course consider a glacier as a frozen river, but the erosive effects of moving ice are much more like those of moving rock masses than they are like those of running water.

Glacial erosion is wholly mechanical, and is accomplished by plucking and sapping or quarrying and by grinding or corrasion and

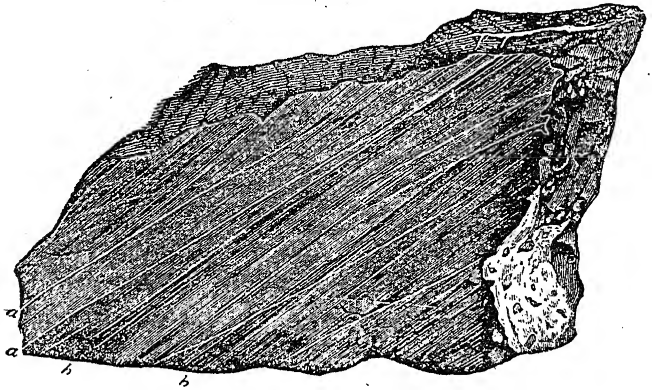


Fig. 358. — Limestone polished, furrowed, and scratched by the modern glacier of Rosenlaui, Switzerland. (After Agassiz, from Lyell.) *aa*, white streaks or scratches caused by small grains of flint frozen into the ice; *bb*, furrows.

abrasion (see Chapter XIV). In addition to this a newly formed glacier will perform denudation or the removal of the material which had accumulated by weathering and otherwise on the surface over which it moves, and prior to its formation or advent. This is the most important erosive work of a glacier in the early stages, while later, quarrying (plucking and sapping) and corrasion become the chief erosive work of the ice. In general, the loose material en-

countered is removed by becoming incorporated in the basal portion of the ice through the freezing of the moisture which saturates this material. In quarrying, the ice mass freezes to projecting rocks or in fissures, surrounding such a projection, and in its movement tears or plucks the rock away. In the performance of corrasion the rock material, frozen firmly into the base of the ice, scratches and polishes the rock floor over which it moves. If the motion is uniform, series of parallel scratches are formed, which indicate the direction of ice movement (Figs. 358, 359, 360 *a*).

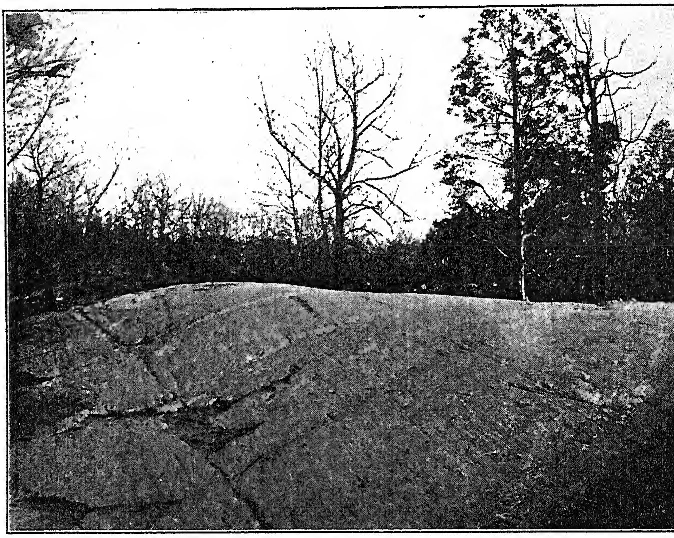


FIG. 359. — A glaciated surface of gneiss, Bronx Park, N. Y. The bands extending across the surface from the lower left-hand side are the gneissic bands; the glacial striæ run nearly at right angles to these. (Photo by Willis; from U. S. G. S.)

The fragments which the ice uses as tools are themselves affected by this corrasive process. The sands are ground and crushed to fine rock flour, which is one of the most characteristic types of material produced by glacial erosion. This must be distinguished from clay or the similarly fine material due to atmospheric decomposition. Under the ice there is little or no opportunity for chemical decomposition, and even after this rock flour is carried away by glacial streams, which it renders turbid or milky, and is deposited elsewhere, it may not undergo decomposition except near the surface. Rock flour, therefore, though resembling clay

in fineness, is distinct from it. Its minute grains may consist of a variety of minerals, according to the rock from which it was derived.

The larger rock fragments are ground and polished upon their surfaces, partly by being dragged over the rock-bottom and partly by the movement of the sand-laden ice over them. If the rock fragments were originally flat, they will be polished and striated only on the two larger faces, the others remaining more or less angular (Fig. 360 *b*). If the fragments are of approximately equal dimensions in all directions, they may have turned over frequently, and

FIG. 360 *a*. — Photograph of a pebble from Permian glacial deposits near Jaquariakyva, Parana, South Brazil. This is a fragment of the old pre-Permian rock floor, showing its glacial striæ. (Courtesy of Prof. J. B. Woodworth.)

FIG. 360 *b*. — A small glaciated boulder from the Pleistocene till. About one half natural size. (Photo by B. Hubbard.)

all sides may be polished and striated. Unless subsequently worn by water, such striated rock fragments constitute a characteristic feature of the deposits formed by glaciers and will lead to the identification of such deposits even after consolidation (Fig. 419). It should, however, be remarked that in talus slides and under certain other conditions, rock fragments may be polished and striated, but they will never be so perfect nor so abundant as those produced by glacial activities.

Glacially produced débris never rests where formed, but always suffers more or less transportation, partly by the ice itself and partly by the streams formed from the melting of the ice. This will be more fully discussed in the next chapter.

Rock Destruction by Organisms

If we except man, who is by far the most powerful agent active in the destruction of the rocks of the earth's crust, we must confess that organisms play but a minor rôle in the destruction of rocks. True, there are certain bacteria which appear to be very active agents in bringing about the weathering of rock surfaces, and the decay of plants furnishes both carbon dioxide and humic acids, which are powerful agents in rock-solution, but aside from this the destructive work of organisms is slight. Plants, whose roots grow in fissures in the rock, will by continued growth force the walls of the fissures apart and so perform a certain amount of superficial destruction (Fig. 33, p. 81). Great herds of animals, too, perform a certain amount of surface destruction by pounding the rock to powder under their hoofs, along the paths of their migration and especially around drinking pools. Such destructive work performed by herds of cattle in Hereroland, former German Southwest Africa, has been described as follows by Pechuel Loesche:

"In extensive manner these animals aid in the leveling of many land areas. As the dryness increases, the herds of grazing cattle become more numerous around the last of the sparsely distributed water bodies. Thousands and tens of thousands of the large and the small animals overrun for miles the surrounding country for days, weeks, and months. Through countless hoof-beats the ground is loosened and so furnishes enormous masses of dust, while at the same time all inequalities are trampled down and destroyed. The inclined surfaces would be furrowed by numerous rain water gullies if these were not constantly destroyed by the hoofs of the roaming animals and if it were not for the fact that rain water is constantly guided along the paths formed by the animals going to and from the water in long lines, ranged one behind the other. Furthermore, the cover of dust prevents to an astonishing degree the penetration of the short heavy downpour of rain into the deeper strata."

This loosening and pounding of rock to dust becomes an effective agent in the lowering of the surface, because the finer particles will be constantly removed by the winds, and it is not too much to attribute to the destructive work of great herds of animals in semi-arid regions the principal rôle in the lowering of the land over large areas and the production of gently inclined planes free from furrows, above which project remnants of the older surface in the form of butte-like hills or ridges. Such "island hills," as they are called, abound in the great Kalahari desert region of Central Africa. The work of burrowing land animals, such as the moles, prairie

dogs, etc., also aids to a certain extent in the further destruction of unconsolidated material.

When we come to the smaller land animals we must note especially the worms and the ants and termites which produce a superficial loosening and rearrangement of the unconsolidated material of the earth's crust, but perform relatively little destructive work in the solid rocks. The many galleries produced by ants and termites admit the air to the soil and so favor decomposition, while organic matter carried down by these animals furnishes acids for the solution of rock particles.

In the sea, too, animals effect a certain amount of rock destruction. Thus many fish, feeding upon growing coral polyps, crop off the coral ends with the polyps and grind the coral to powder, which eventually passes from them as lime flour. Calcareous algæ or nullipores are also ground up in this manner. Crabs, and other crustaceans also, break up shells of mollusks and echinoderms on which they feed, and so produce a not inconsiderable quantity of shell fragments which will enter into the construction of new limestones. Other marine animals active in this way are the echinoids, which destroy rocks to a certain extent, by drilling holes in them; but their work as rock breakers is of moderate significance.

CHAPTER XVI

TRANSPORTATION, SORTING, AND DEPOSITION OF CLASTIC ROCK MATERIAL

Only the clastic material due to weathering may remain in the place where it is produced or suffer only slight shifting of locality, before becoming reconsolidated into a rock, which then will be unassorted in respect to material, and essentially without structure. Such old soils, subsequently changed to rock, are found in some localities, but for the most part the product of weathering is transported and redeposited elsewhere, and in this process undergoes more or less sorting, while new structures incident to these modifications are impressed upon it.

Agents of Transportation and Sorting and Regions of Deposition

Transportation. — The chief agents of transportation of clastic material are wind, and water currents, both those of rivers and those of the sea. Glaciers, however, and floating icebergs also transport clastic material, though much of that transported at first by glaciers is subsequently carried farther sometimes by water, and sometimes by wind. There are of course minor agents of transportation, among which may be mentioned other floating structures, such as vegetation, etc., to which various kinds of rock material are attached; snow and landslides, and animals which carry rock material either attached externally or in their stomachs. Man is of course the most effective agent of transportation, calling to his aid the resources of wind, water currents, steam, electricity, and animal energy; but he works, as yet, upon a far smaller scale than do the less efficient rivers, winds, waves, and ice.

Sorting. — Both wind and running water accomplish sorting of material, and the waves of the sea and lakes are also active in this respect. Glaciers and icebergs, on the other hand, transport material without sorting it in any way.

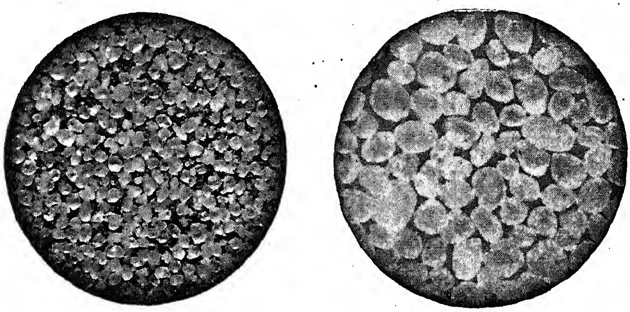
Deposition. — Deposition of clastic material takes place in the sea (marine deposits), in lakes and ponds (lacustrine deposits), and on dry land (terrestrial deposits). The last two types are often designated continental as distinct from marine deposits. Intermediate between the lake deposits, on the one hand, and those of dry dust and sand, on the other, are the deposits formed on river flood-plains and on alluvial fans, while between the terrestrial and marine deposits, the sea-border delta sediments form a transition type.

Transporting and Sorting by Winds

Whatever the origin of clastic material, if it is light enough and small enough in grain, it can be transported by wind. As we have seen, the removal, by wind, of loose material from a surface where it has been produced is called *deflation*, and this is the beginning of eolian transport. Such transport is accomplished either by carrying the material in suspension as in sand and dust storms, or by rolling and pushing it along over the surface without lifting. Only fine material such as dust can be retained in suspension for any length of time, and thus be carried far. The volcanic dust produced by the explosion of Krakatoa, in 1883, referred to in Chapter VII (p. 137), was carried by the upper air currents repeatedly around the earth before settling. But even pebbles, 8 mm. in diameter or larger, may be picked up by a strong wind and carried a short distance. Much larger sand grains and pebbles may of course be rolled along the surface than could be lifted by wind of the same strength.

Both the material which is carried in suspension and that which is rolled along by the wind become assorted according to size and weight of grain, the latter varying, of course, for particles of the same size according to their mineral character. The smaller grains are picked out and carried farthest; the larger ones settle out earlier. The lighter minerals too are carried far, leaving the heavier behind. Thus after repeated transportation by wind, the material will become well sorted, only grains of about the same size and of the same mineral character accumulating at any given locality. In this process of transportation the grains will also be more or less worn and rounded by mutual abrasion, as already described (p. 406).

When an older sand deposit consists of well-rounded grains of uniform size and of only one mineral species, the supposition is very strong that such a deposit represents the work of the wind at a former time. A rock formed of such material, and known as the Sylvania sandstone of Silurian age, occurs in Ohio and Michigan. The grains are wonderfully well rounded (millet seed type); they are of essentially uniform size in each locality, though those of one locality may differ from those of another, as is shown in the two photographs (Fig. 361 *A*, *B*) which represent grains from different localities, enlarged to the same degree. They consist wholly of



A *B*

Fig. 361. — Microphotographs of Sylvania sand grains, enlarged about 11 times. *A*, from National Silica Co., Monroe county, Mich., near top; *B*, from Rockwood pits, four feet down, American Silica Co. The grains are well rounded and of nearly uniform size, but differ in size in the different localities. (W. H. Sherzer, photo; from Grabau and Sherzer, *Monroe Formation of Michigan.*)

quartz without any foreign admixture. This fact and the ready separation of the grains makes the rock valuable for glass manufacture. This rock has been interpreted as formed of wind-transported, wind-sorted, and wind-worn sand grains, and the larger structural characters of the deposit bear out this hypothesis. (See Fig. 374, p. 455.)

Dust and Sandstorms (Fig. 362). — All deserts are subject to violent sand and dust storms, when the strong wind picks up the dry material from the surface and whirls it along in a cloud, which may appear like a solid moving wall. After such a storm the air will be hazy with dust for a long time, and indeed in some desert regions the air is seldom free from suspended dust. As the wind dies down, the coarsest material settles first, the finest being long

held aloft and carried far. Sandstorms may be very destructive to life, and as a result of their occurrence great changes in the aspect of the country are produced. To this constant motion of the sand and dust, as much as to the absence of moisture, is due the general lack of vegetation in the sandy desert (Figs. 363 *a*, *b*).

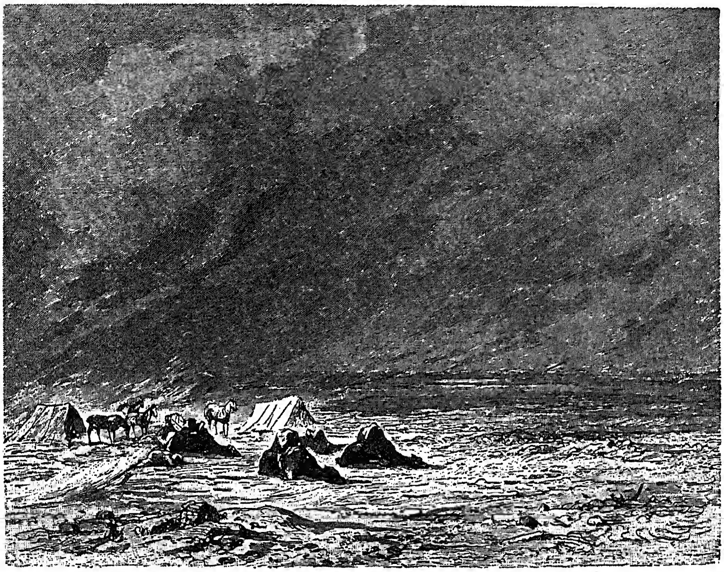


FIG. 362. — Sandstorm in the Sahara; from nature. (After Ratzel.)

Distances to which Sand and Dust are Transported. — The distance over which material is transported depends not only upon the size and weight of the particles and the strength and continuity of the wind, but also upon the initial position of the material. When dust is projected high into the air, as by volcanic explosions, the force of the wind is wholly employed in carrying it, and hence such substances will be transported farther than those picked up by the wind directly. As already noted, the fine dust of Krakatoa was repeatedly carried around the world, and its suspension in the upper air caused everywhere the brilliant sunsets for which the period following the eruption was noted. The coarser ashes fell inches deep at a distance of a thousand miles from the volcano, and some even fell in Holland. Volcanic dust from Iceland has fallen repeatedly in Scandinavia, Holland, and northern Britain. Dust

from the Sumatran volcano, Tomboro, has fallen a thousand miles away, and dust from the Mexican volcano, Colima, fell in February and March, 1903, at points more than 200 miles northeast of the volcano.

FIG. 363 *a*. — View of a portion of the Desert of Sahara.

The ash from the eruption in 1835 of the Nicaraguan volcano, Cosequina, covered an area of 1,500,000 square miles, and even reached Jamaica, more than 750 miles away. Dust from the eruption of Mont Pelée in 1812 is said to have reached the Azores on the other side of the Atlantic, and dust from Vesuvius has been observed to fall in Greece, in France, and in Austria.

Dust of non-volcanic origin is also carried to great distances. Some known to have been derived from the Sahara, was repeatedly

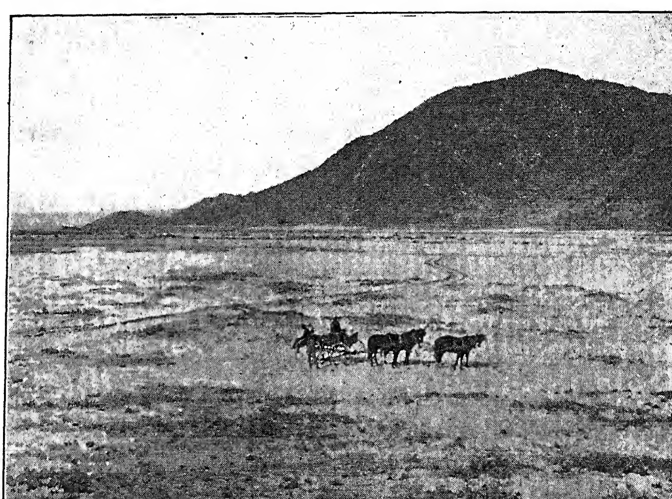


FIG. 363 *b*. — General view in the arid region, western North America.

carried across the Alps and fell in such distant regions as England and North Germany, 2000 miles away. Dust from Australia sometimes reaches New Zealand, 1500 miles away, and yellow dust from the interior of China has fallen on the decks of vessels southwest of Japan, having been carried at least a thousand miles from its source.

Volume of Dust Falls. — The quantity of dust transported during a single storm may be very great. In 1863 a rain of dust fell on the Canary Islands which was estimated to have a weight of 6,500,000 tons. The great dust storm of March 9–12, 1901, brought 1,960,000 tons of dust to Europe and 1,650,000 tons to North Africa, covering a total area of 300,000 square miles of land surface and 170,000 square miles of ocean. It was estimated that this dust traveled, in part at least, a distance of 2500 miles. It is thus clear that wind-transported material plays an important rôle in nature.

Deposition of Wind-blown Sands

Wind-blown material may be deposited in water or upon dry land. Only the latter has distinctive characters, for the former is incorporated with other water-laid (lacustrine or marine) clastics. The most characteristic types of wind-borne sand deposits are the dunes. These are found on most coasts, but also abound inland, especially in desert regions, where they often assume considerable proportions and cover wide areas.

Types of Sand Dunes

Three main types of sand dunes are recognized: (*a*) the conical hill, (*b*) the linear, and (*c*) the curved or crescent-shaped type, known as the *barchane* (Fig. 368). Between the last two are often combination types which have some of the characters of both. The linear type is most common on the coast, where a uniform and constant supply of sand is furnished; while the crescent-shaped or barchane type is most characteristic of the interior, the river flood-plains of arid regions, and the deserts. According to location, dunes may be classed as (*a*) coastal, (*b*) river-bottom and flood-plain, and (*c*) inland or desert dunes.

Coastal Dunes. — These are chiefly of the linear type and extend in general at right angles to the prevailing wind. They always have an asymmetrical cross-section, the opposite sides sloping

at decidedly different angles. The side toward the coast, exposed to the direct force of the wind, generally has a slope of only about 10°; the angle of the opposite or leeward slope is often as high as 30°. Sand grains are rolled up the windward side, and passing the crest of the dune, roll down upon the lee slope. Thus the dune slowly advances in the direction in which the prevailing wind blows, which, being from the sea, causes the dunes to move inland at a very variable rate.

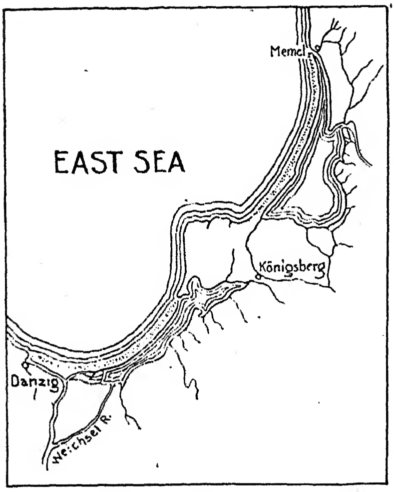


Fig. 364 *a.* — Map of the region between Danzig and Memel on the East Sea or Baltic, Eastern Germany, showing the Kurische Nehrung (or bar) and Kurische Haff (or lagoon) north of Königsberg, and the Frische Nehrung and Frische Haff south of Königsberg. These are typical examples of dune covered sand bars enclosing lagoons.

The advancing sand dunes bury whatever lies in front of them. The dunes formed on the barrier beaches of our coasts advance over the salt meadows formed in the lagoon behind the bars (see p. 330). In long-inhabited coastal regions, the dunes may cover buildings and even villages. The dunes of the North Sea coast of Denmark and Schleswig-Holstein, which cover an area of 165,557 acres, and rise in places to a height of nearly a hundred feet, furnish a good illustration of this phenomenon, especially as the coast here is also cut back rapidly by the sea, and the region is believed to be subsiding. In 1757, it was found necessary to tear down the church of the village of Rantum on the island of Sylt, on the west coast of Schleswig-Holstein, because it was reached by the advancing dunes. In 1791 or 1792, the entire dune chain had passed over the church ruins, these then lying on the shore, which had advanced to this point. Sixty years later, the site of the church was 700 feet from shore, the depth of water at that point being 12 feet. The second church has since been buried by the advancing dunes.

On the east shore of the Baltic (East Prussia) are two long sand

bars, the Kurische and the Frische Nehrung, which separate large lagoons, the Kurische and the Frische Haff, from the Baltic (Fig. 364 *a*). These bars are covered with extensive sand dunes, some

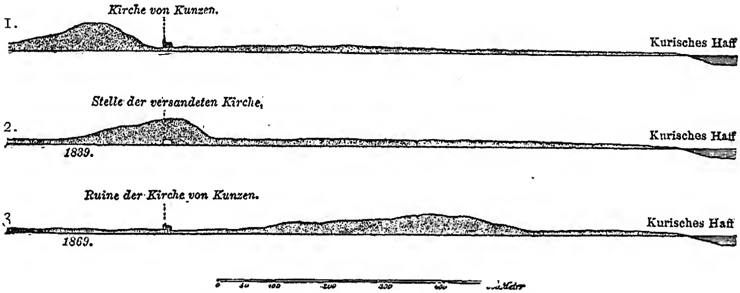


FIG. 364 *b*. — Diagrams showing the advance of the coastal dunes over the village and church of Kunzen on the Kurische Nehrung (bar), from the east shore of the Baltic Sea to the Kurische Haff (barachois). (1) At the beginning of the nineteenth century, when the dunes had just reached the church of Kunzen. (2) Conditions in 1839, when the church was buried by sand. (3) Conditions in 1869, when the dunes had passed beyond the village site, uncovering again the ruins of the church. (After Behrend; from Ratzel.)

of which reach a height of sixty meters or more, being among the most imposing dunes of the European coast. Between the years 1809 and 1869 the dunes of the Kurische Nehrung (bar) in their

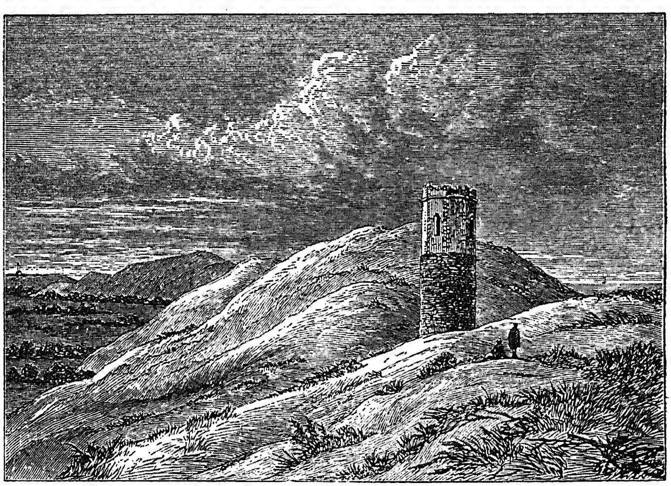


FIG. 365 *a*. — Tower of the buried church of Eccles, Norfolk, England, 1839. The inland slope of the hill of blown sand is shown in this view, with the lighthouse of Hasborough northwest of the tower in the distance. (See Fig. 365 *b*.) (From Lyell's *Principles*.)

advance buried the church of the village of Kunzen by passing over it and later resurrected it by migrating further inland (Fig. 364 *b*). An analogous phenomenon has been observed on the coast of Norfolk, England, as shown in the next two figures (Figs. 365 *a*, *b*).

The largest dune area of the European coast, and one of the largest coastal dune areas known anywhere, is on the western shores of France, along the Bay of Biscay. The dunes extend almost

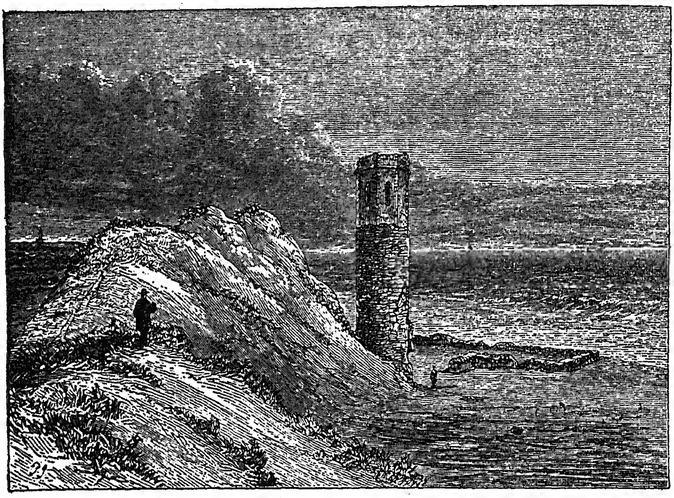


FIG. 365 *b*. — Eccles Tower as it appeared after the storm of November, 1862. From a drawing by Rev. S. W. King, taken from nearly the same position as Fig. 365 *a*. (From Lyell's *Principles*.)

without interruption for a length of 240 km. and lie in parallel rows up to ten in number, over a coastal strip from four to eight, and in some cases 10 km. wide, covering a total area of 120,000 hectares (296,520 acres). In height the dunes range up to 90 meters, making them the highest known coastal dunes, though some inland or desert dunes which have advanced toward the coast in North Africa reach twice this height.

Behind the great Biscayan dune belt lies the low, swampy tract known as the *Landes*. The dunes travel inland at a rate ranging from 15 to 105 feet per year, burying not only the swamp lands, but forests, farms, vineyards, and even villages. The church at Lège was taken down at the end of the seventeenth century and rebuilt two and a half miles farther inland. One hundred and sixty

years later it had to be removed again, because the sands had once more reached it. This gave an average rate of advance for the dunes of 81 feet per year. The sea, too, advances, cutting back the coast in places at the rate of not less than 2 meters per year.

The dunes on the Atlantic coast of North America are mostly of inferior size and formed in connection with off-shore sand bars. At the extreme end of Cape Cod, however, where the waves have built the series of bars which form the foundation of the Provincetown dune-lands (see Fig. 714), great sand dunes, some of them

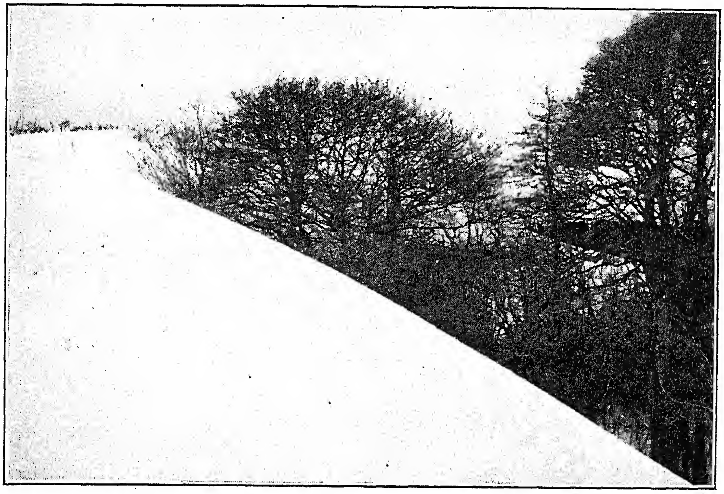


Fig. 366 *a*. — Dune of barchane form overwhelming trees on the Provincelands of Cape Cod. The top branches of a tree protrude from the crest of the dune. (D. W. Johnson, *Shore Processes and Shoreline Development;* John Wiley & Sons.)

exceeding 30 or 40 meters in height, have been formed by the wind. These dunes slowly advance southward and westward, burying forests and even buildings in their advance (Fig. 366 *a*). Their movement has, however, been checked to some extent by the planting of grasses and shrubs on the windward slopes. Between the years 1826 and 1838, some $28,000 were spent in this work of arresting the dunes. The dunes of the Virginia and Carolina coasts are also of considerable magnitude, and they, too, bury forests and whatever else lies in the path of their advance (Fig. 366 *b*).

In the mastery of sand dunes by means of skillfully planted vegetation France, Belgium, Holland, Germany, and other countries

have far outstripped America, because the lands in the old world coastal district are far more valuable on account of the denser populations.

On the shores of the Great Lakes, dunes are likewise well developed. The most extensive dune area lies on the eastern and southern shores of Lake Michigan, and some of the dunes there rise to the height of a hundred feet, especially in the Dune Park area of Indiana. A dune near Muskegon, Michigan, has a height of several hundred feet, and from its rate of advance has become known as "Creeping Joe." Many of these dunes are grassed over

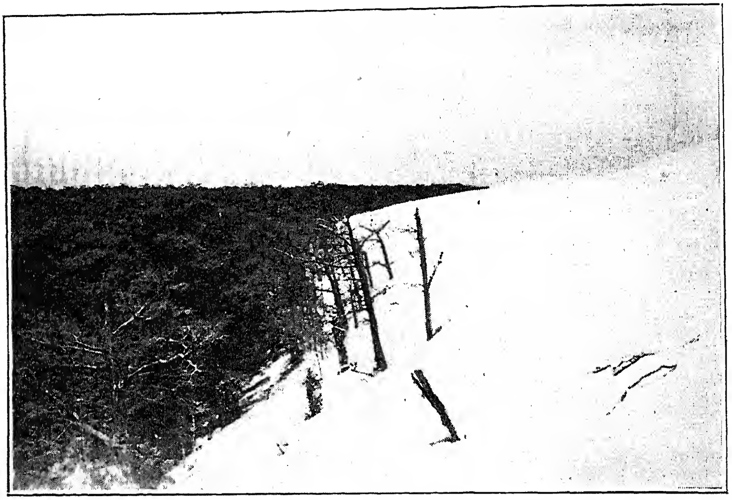


FIG. 366 *b*. — Shore dunes near Cape Henry, Virginia, migrating inland over the forest. (D. W. Johnson, *Shore Processes and Shoreline Development;* John Wiley & Sons.)

and even wooded, but they are still recognizable by their form. Others are in active motion, burying and killing forests and again uncovering them in their advance. In many cases only the very tops of the trees now project above the surface of the dune. The sand of these dunes is chiefly of glacial origin.

River-bottom and Flood-plain Dunes. — In semi-arid regions the rivers partly dry away during the summer season, leaving broad flood-plains and river-bottoms covered with the sands brought down by the rivers. These sands are then heaped into dunes by the winds and travel across the country, sometimes from one river-bottom to another. Such dunes are extensively developed along

the river borders in the semi-arid regions of southern Russia; as, for example, along the Dnieper, the Don, and the Volga, where they occur in belts sometimes as wide as 30 kilometers, and have a length of 150 kilometers or more. The dunes are seldom more than five to seven meters in height, though some reach a height of 12 meters or more.

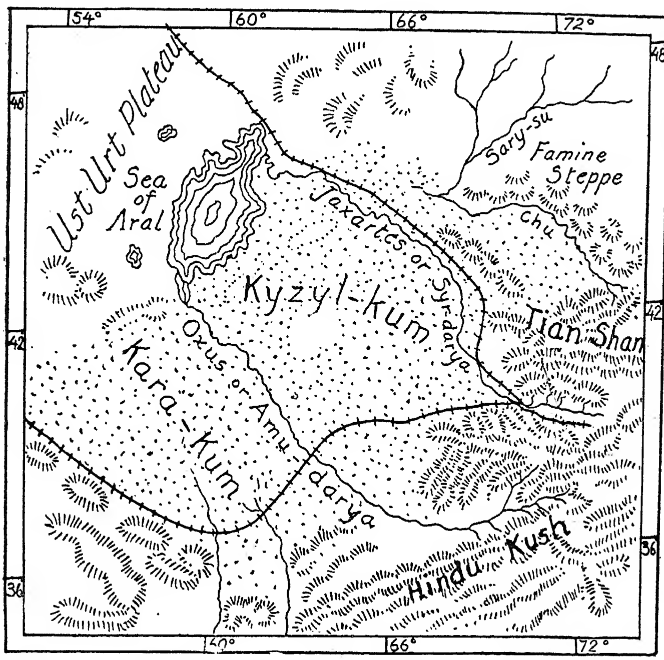


Fig. 367. — Outline map of the drainage region of the Oxus and Jaxartes rivers (Amu-darya and Syr-darya) and the deserts of Kyzyl-Kum and Kara-Kum.

As typical examples of river-bottom dunes may be cited those of the rivers Oxus and Jaxartes in Turkestan, Central Asia, both of which flow into the Aral Sea. "These streams bring vast quantities of sand and mud from the Tian Shan, Great Pamir, and Hindu-Kush mountains, in which they arise, and spread them over the low ground of their flood-plains, which range in width up to ten kilometers. The thickness of the deposit made by the Oxus was found to be 23 meters at Tschard-schui. The rivers rise three meters from March to July, and overflow the flood-plains, depositing sandy sediment. As the water of the Jaxartes falls, the hot

northern winds soon dry the deposit and carry away all the finer dust particles, leaving only the pure quartz sand, which is heaped into dunes. These wander southward across the Kyzyl-Kum desert [Fig. 367], sometimes at a rate of 20 meters during a stormy day, but generally the sand masses move at an average rate of six miles per year. Reaching the Oxus, these sands are incorporated in its sediment, and the operations of sorting the deposits on the flood-plain of this river are repeated, and the sands are again heaped into dunes which wander southward across the Trans-Caspian or Kara-Kum desert until they reach the borders of the Caspian Sea. The activities of the streams are unceasing, and the supply of material in the mountains in which they rise is practically inexhaustible. Thus there is a constant succession of sand dunes wandering southward across these deserts, and layer upon layer of sand accumulates, each showing the characteristic eolian structures and helping to build up a deposit of pure, unfossiliferous sand of almost unlimited thickness."[1] Large sand dunes are also found on western American river-bottoms, such as those of the Columbia (Fig. 368) and Snake rivers in Oregon and Washington.

The dunes of these river bottoms and intervening deserts are both of the linear and the crescent-shaped type. The linear dunes are generally symmetrical in section and extend parallel to the direction of the wind, where this is strong and the supply of sand large. They may, indeed, be regarded in many cases as the extended horns of the crescent or barchane type.

Desert Dunes.—In deserts the barchane or crescent type of dune is most typical. When best developed, this presents a crescent form with the convex side to the wind and its surface a gentle slope (Fig. 368). The lee side is steep and abrupt, with a concave outline, from the ends of which the horns extend in the direction of advance. By an elongation of these horns, when much sand is supplied and the winds are strong, long, parallel ridges, united at intervals by cross ridges, may be produced, their direction running parallel to that of the wind.

The great desert dune districts are found to-day in Asia, Africa, and Australia. Dunes cover only one ninth of the total area of the Sahara, but even this aggregates a total of 18,000 geographical square miles. Arabia is *par excellence* the land of desert dunes, nearly one third of the entire surface, or not less than 15,000

[1] A. W. Grabau, *Principles of Stratigraphy*, p. 561.

geographical square miles, being covered with sand. Almost the whole southern area is occupied by the terrible Desert of Roba-el-Khali, or the desert Dehnā, which is wholly covered by eolian sands, and is without the relief of oases. This desert is 150 geographical miles in length and 80 in width. In the northern part of the peninsula lies the Nefud Desert, where the sands are red and water practically absent.

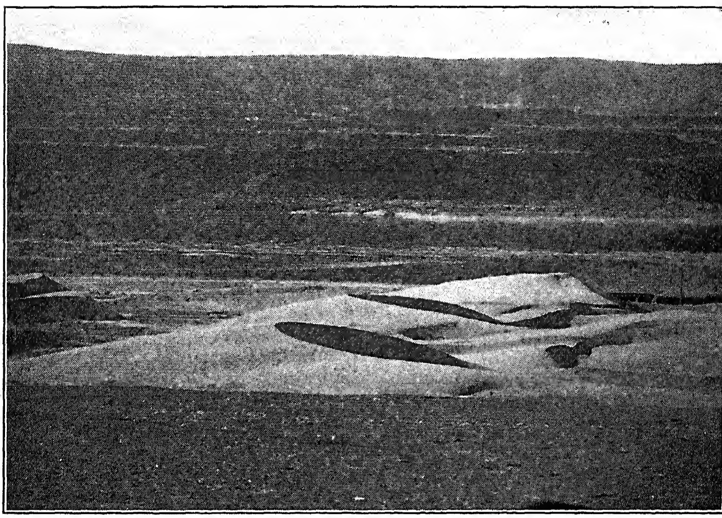


Fig. 368. — Sand dunes of the barchane type in the valley of the Columbia River, near Biggs, Oregon. River terraces shown in the background. (Photo by Gilbert, U. S. G. S. Courtesy of D. W. Johnson.)

Sandy deserts exist in many parts of Asia, and the whole interior of Australia is a desert, many parts of which are covered with drifting sands. Sandy deserts also abound in southwestern North America, especially in southern California and Arizona. Almost one fourth of the state of Nebraska, or about 18,000 square miles, is covered with drifted sands, forming the "Sand Hills" region with its many lakes, from some of which potash salts are extracted. These lakes are the result of a change in climate from dry to moist, in consequence of which the old dunes are mostly covered with vegetation, though many fresh hollows or "blowouts" occur. In the central plains of Hungary, too, are many old sand dunes now covered with vegetation, but readily recognizable by their form.

The sands of many deserts are derived from the disintegration of older sandstones; as, for example, the sands of the Libyan Desert, which are derived from the Nubian sandstone, and from a younger

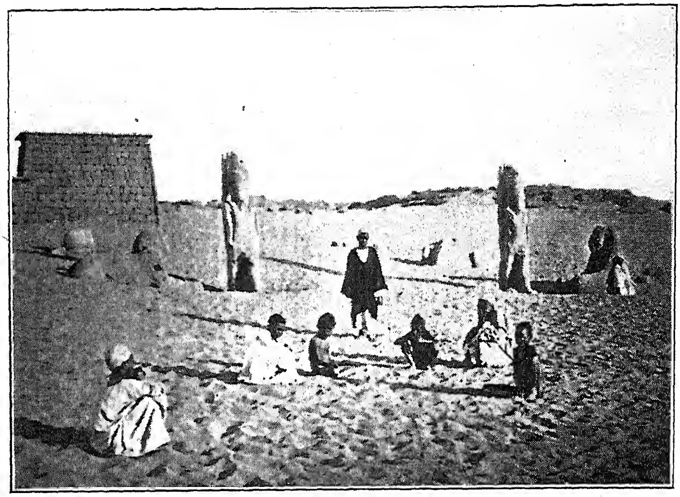
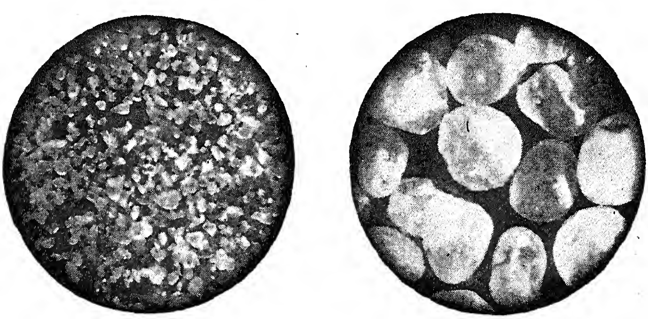


FIG. 369. — The edge of the Libyan Desert.

rock from which the Sphinx is carved. This sand (Fig. 369) has been carried in places for a hundred miles from its source, and often rests upon old limestone surfaces, the weathered-out fossils of which it encloses in its basal portion. From long transport



A *B*

FIG. 370. — Microphotographs of sand grains from the Libyan Desert, enlarged about 11 times. *A*, finer sand only partly rounded, due to constant accession of new material; *B*, coarser grains (mechanically separated), showing pronounced rounding and relative uniformity of size. (W. H. Sherzer, photo; from Grabau and Sherzer, *Monroe Formation of Michigan.*)

the sand is well sorted according to size of grain and purity of material, and from wear the grains are well rounded (Fig. 370, *B*). Where much fresh material is furnished by local disintegration of rock, a certain amount of angularity of the smaller grains is still seen (Fig. 370, *A*). The more perfectly rounded grains are similar to those of the Sylvania sandstone of Silurian age (Fig. 361, p. 440).

Structure of Sand Dunes

Ripple Marks. — We have seen that the wind carries the sand up the gentler side of the dune, and that it rolls down the steeper side. The progress of the sand on the windward side is commonly shown

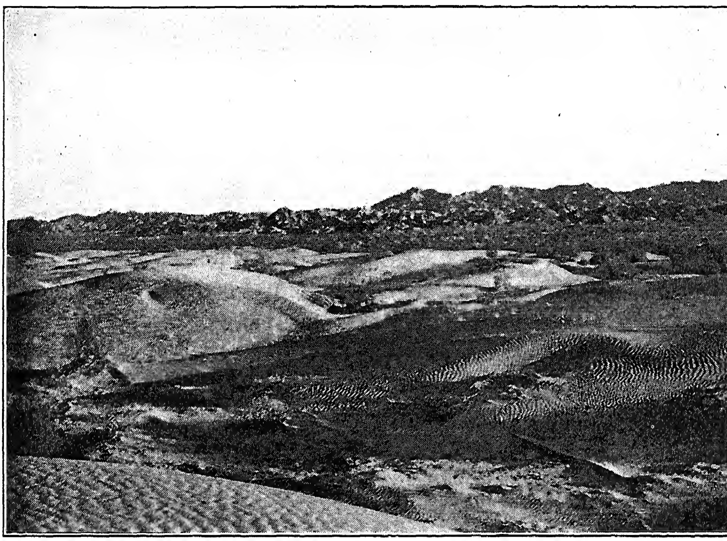


FIG. 371. — Typical sand dunes with ripple marks in desert region of southern California, Colorado Desert. (Photo by Mendenhall, U. S. G. S. Courtesy D. W. Johnson.)

by ripple marks of an asymmetric character (Fig. 371), these being in reality secondary dunes of minute size upon the surface of the larger ones. The following diagram shows types of ripple marks observed in desert sands (Fig. 372 *a*).

Cross-bedding of Dunes. — With different velocities of the wind, particles of different size will be deposited upon the slopes, and thus layers of different texture will be formed, which may appear distinctly in a section of the dune. These layers have a gentle

slope on one side and a steeper one on the other, and at the base of the dune the gentler sloping layers will gradually pass into a

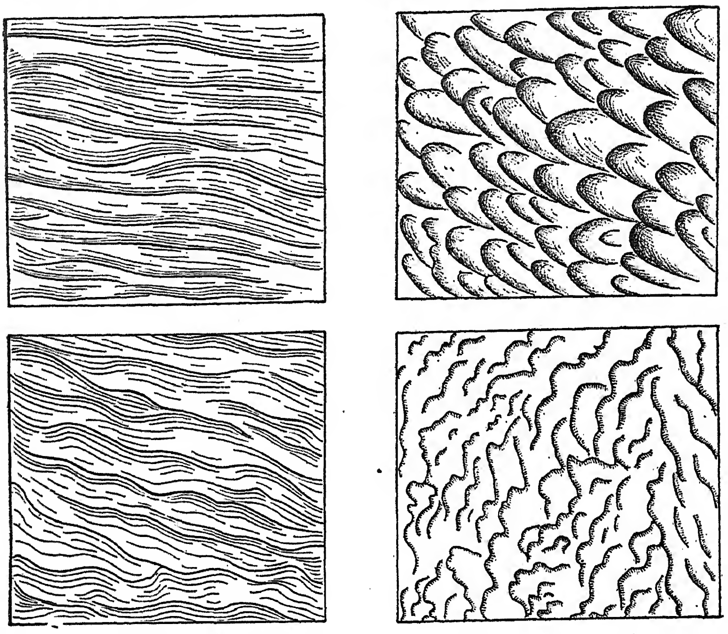


FIG. 372 *a*. — Various types of ripple marks in Lop-Nor Desert, Turkestan. (After Sven Hedin, *Scientific Results of a Journey in Central Asia.*)

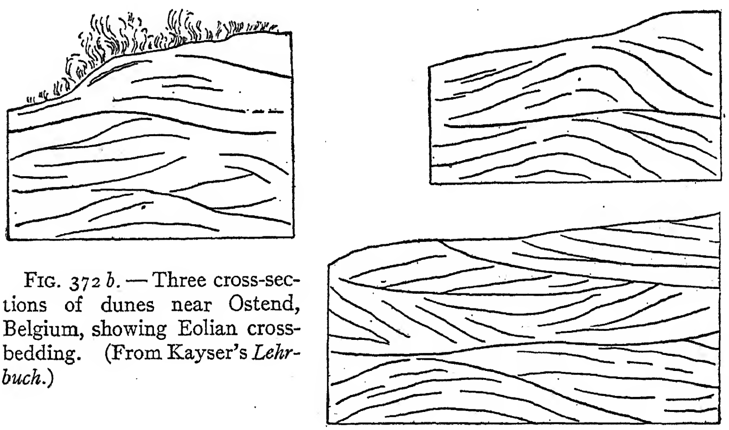


FIG. 372 *b*. — Three cross-sections of dunes near Ostend, Belgium, showing Eolian cross-bedding. (From Kayser's *Lehrbuch.*)

horizontal position. If now by a change in the direction or force of the wind a part of the dune is cut away again, the remaining

basal portion will present layers which slope in two directions and will be abruptly truncated above by a horizontal or oblique erosion plane. A second dune deposited above this remnant may become so placed that its layers slope in the opposite direction, or at a different angle from those beneath it. Thus will be formed a type of *cross-bedding*, as it is called, in which there are successive divisions of the mass, separated by erosion lines, and with the layers of each division dipping in one or more directions without reference to the dip of the layers in other sections. The preceding illustration represents actual cross-sections of dunes near Ostend, and shows the result of such repeated partial destruction of older, and deposition of newer, dunes, and the wind or eolian cross-bedding thus formed (Fig. 372 *b*).

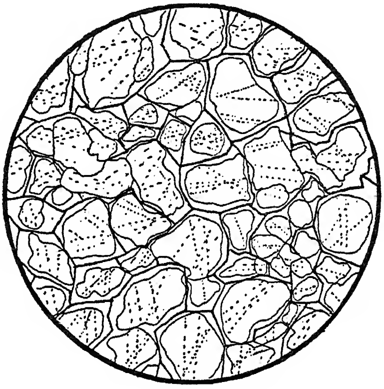


FIG. 373. — Thin section of quartz sandstone shown under the microscope. The original rounded quartz grains are surrounded by new quartz (secondary enlargement), forming a quartzite, Hauptbuntsandstein, near Heidelberg; enlarged 12 diameters. (After Rosenbusch.)

Ancient Deposits with Eolian Cross-bedding. — Many ancient sandstones show a cross-bedding of this type, from which it may be inferred that they represent older dune deposits now consolidated. As such dunes are at present most characteristic of and most extensive in desert areas, we are led to conclude that the deposits in question, if at all extensive, were formed under similar circumstances. For corroborative evidence, the character of the grains must be examined, since in typical eolian deposits these should be more or less well rounded, assorted according to size, and essentially of the same mineral substance. The original roundness of the grains may be obscured by the subsequent deposition around them

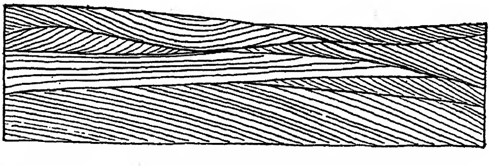


FIG. 374. — Cross-bedding in Sylvania sandstone.

of mineral matter of the same character, so that they appear angular. Such *secondary enlargement* of the grains, as it is called, can generally be detected under the microscope (Figs. 373, 472).

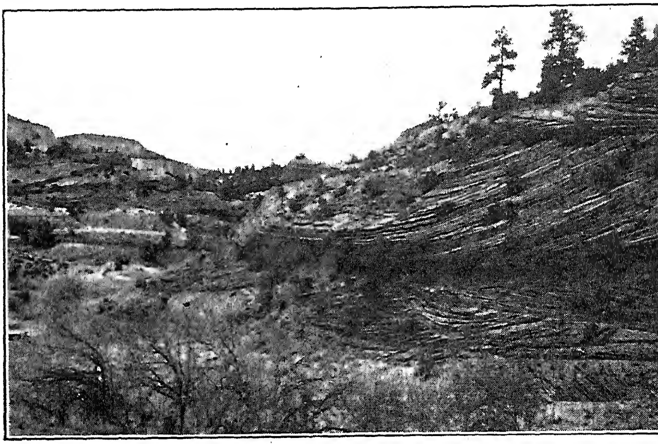


FIG. 375. — Eolian cross-bedding in Mesozoic sandstone, Little Meadow district, Utah. (Gardner Collection of Photographs. Courtesy of the Geological Department of Harvard University.)

Eolian cross-bedding is well shown in the Sylvania sandstone, above referred to, as having the characteristic grains of eolian deposits (Fig. 374). Eolian cross-bedding is strikingly shown in the Jurassic sandstone which forms the White Cliff of the Colorado Plateau and in other sandstones of western as well as eastern North America. This seems to point to the eolian origin of these rocks (Figs. 375, 376).

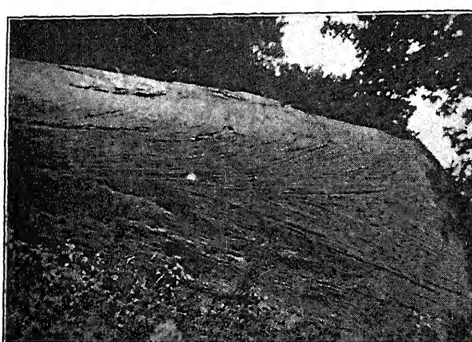


FIG. 376. — Large boulder of sandstone showing Eolian cross-bedding, Mt. Pisgah, Greene County, N. Y.

Possible Sources of Error. — It should, however, be borne in mind that only when such cross-bedding is developed on a large scale and over a wide extent can it be regarded as indicative of eolian deposition. When restricted to a narrow

area, it may be due to the cross-bedding produced in sand bars along the coast. As will be shown later, this is of limited extent only. Cross-bedding of this type, but with the successive divisions

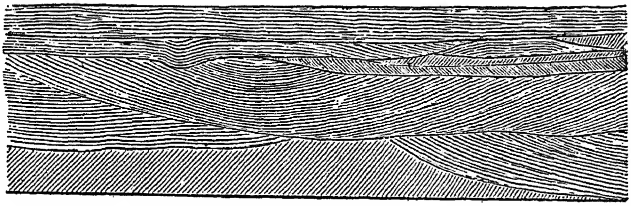
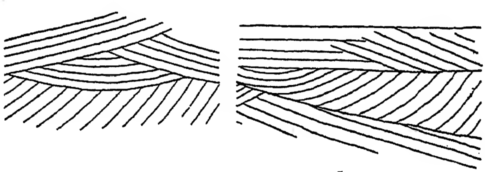


FIG. 377. — Cross-bedding of the Eolian type in the Orange sand or La Fayette Formation, Mississippi Central Railroad, Oxford, Miss. (After Hilgard.)

measuring inches rather than feet in thickness, can also be produced by successive current ripples such as may be formed upon the bottom of a shallow water body. Cross-bedding on a large



a *b*

FIG. 378. — Eolian type of cross-bedding in ancient limestones (Mississippian), formed of uniform lime-sand grains (calcarenyte) south of St. Louis, Mo. Scale, 1 inch = $3\frac{1}{3}$ feet. (From *Principles of Stratigraphy.*)

scale cannot, however, be produced in this manner. The preceding illustrations show such cross-bedding on a large scale, in unconsolidated older sands (Fig. 377), and in ancient limestones (Fig. 378).

DUST DEPOSITS

Mode of Deposition. — Dust-laden wind sweeping across a steppe land, where herbaceous vegetation grows in a scattered manner, will have its velocity checked when it comes in contact with this vegetation, and a part of its dust load will be dropped. This will accumulate around the plants, which thus become buried in the dust deposits essentially in the position of growth. Successive accumulations of dust will raise the surface of the plain until the plants die and new ones take their place. In this manner, thick deposits of dust may be built up.

When dust-laden winds reach a rainy district they are washed clean by the rains, and similar deposits of dust accumulate, but these are likely to be more or less modified by running water or become incorporated in pond or lake sediments.

Character of Deposits. — Unmodified dust deposits, owing to their uniformity and fineness of grain, lack as a rule all evidence of bedding or deposition in layers — *i.e.*, *stratification*. They will form a more or less homogeneous mass of uniform structure throughout.

The Loess an Example of a Dust Deposit

In the eastern part of China, extensive deposits of fine dust-like material have been formed, to which the name *loess* is applied. This dust is believed to have been carried by the wind from the great deserts of the interior, especially the desert of Gobi, and it has accumulated to such an extent that in some sections its thickness is one or even two thousand feet. This loess has a very high fertility, and although its surface has been cultivated for thousands of years without the application of artificial fertilizers, it is still productive, owing perhaps largely to the constant addition of new material. Its extent appears to coincide with the limits of Chinese agriculture. Loess has the property of maintaining a vertical face whenever a section is cut, due largely to the presence in it of vertical tubes which are more or less filled with mineral matter, and which cause the vertical scaling off of layers; thus walls of loess 200 feet in height are produced. Where roads have been worn into it by constant travel and where the material loosened thereby has been removed by wind, these roads lie in canyon-like depressions with vertical walls often of considerable height. In some places in China, caverns are dug into the base of such a wall and occupied as dwelling places by the humbler natives.

Loess is also found in the United States, the material having been supplied by glacial streams during the ice age of a former period. During the drier periods between ice advances (interglacial periods), this dust has been taken up by the winds and deposited in favorable localities. Such deposits frequently include the shells of land mollusks, such as snails (*Helix*, Fig. 256, p. 316), and occasionally those of river border types. (See Figs. 252–255, pp. 315–316.) In it are also found the peculiar little concretionary masses which characterize the Chinese and many European loess

deposits and which have become known as loess dolls (*Loess-püpchen* or *Loessmännchen*), and which were apparently formed at subsequent periods by the concentrative work of ground-water (Fig. 477 *d*, p. 573).

Loess contains a small percentage (4 or 5 per cent) of iron oxide generally in the hydrous form. Being uniformly disseminated through the mass, it gives the loess a yellowish color, and where streams cut into such deposits, their waters are colored by the fine sediment carried along. The Yellow River of China (Hoang-Ho) owes its color and name to such loess sediment carried by it, and the color of the Yellow Sea is likewise derived in this manner.

We can picture to ourselves what would happen if such loess deposits became buried by other sediments laid down upon them, and consolidated into a rock. Such a rock would be of uniform grain and show no bedding structure (stratification), except perhaps at considerable intervals. Moreover, from the gradual effect of aging and of heat, the water of the iron hydrate would be driven off, and the color of the deposit would change from yellow to a uniform red. Thus a bright-red or brick-red rock of uniform fine grain, without bedding planes, would be produced. Ancient rocks of this character are not unknown, and they have sometimes been interpreted as altered loess deposits of a former time. Such rocks are of course as a rule free from the remains of organisms, except that those of terrestrial animals and the seeds and other wind-transported parts of plants may become included in them. The plant remains will tend, by decomposition, to furnish substances which locally change or remove the iron so that white or greenish spots and streaks may mark the otherwise red rock.

The Black Earth of Russia. — Over considerable areas in Russia, the surface of the earth is covered with a loess-like deposit, the upper part of which, for 20 feet or more, is colored black by a thorough admixture of organic matter (Fig. 379). This Black Earth or *Tchernozom* or *Tschernosem*, as it is called, appears to represent the accumulation of fine dust among actively growing herbaceous vegetation, the decay of which furnished the organic matter of the black earth, of which it sometimes forms ten or more per cent. This organic matter renders the soil exceedingly fertile and capable of growing large crops continually without manure. A similar black soil, called the Regur or black cotton soil, occurs in India. Such soils when buried under other deposits and

compacted, become black carbonaceous shales, such as are found throughout the southern states in the late Palæozoic series (Chattanooga Shale), though other interpretations have also been proposed for them.

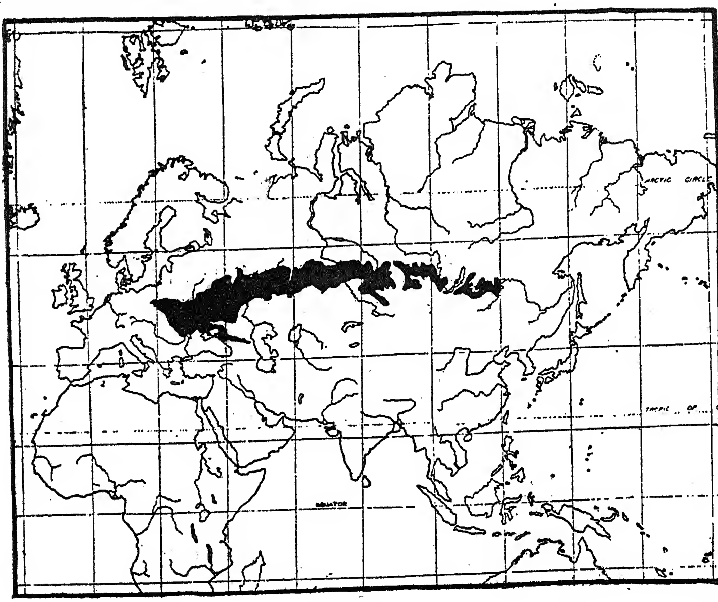


Fig. 379. — Map showing the distribution of the Black Earth or Tschernosem in Russia. (After Glinka.)

Transporting and Sorting by Streams

Transportation of Sediments

Streams are among the most effective agents of transportation. Besides carrying substances in solution, they carry fine particles in suspension, and push and roll larger ones along their bottoms. In this manner material may be transported by streams for hundreds of miles before it finally comes to rest.

Conditions of Transportation. — The materials which streams carry are the products of rock weathering and of mechanical wear, partly produced by the stream itself, and partly supplied by rain water, by rills, and by wind. The power of the stream to carry, roll, or push along material varies with the velocity, and in any given section of the stream this velocity varies as the cube-root of the volume. Thus a stream swollen to eight times its original size will

have its velocity doubled, and therefore its carrying power is increased. This in general varies as the sixth power of the velocity, and therefore, a stream the velocity of which has been doubled will be able to carry sixty-four times the quantity of material which it could transport before.

This may be demonstrated in the following manner (Fig. 380). Given, a current which can just move along a cube of rock (*a*) of a certain size. If the velocity were doubled, twice as much water as before would strike the cube in a given time, and with twice the force. Therefore, such a current would move along four such cubes placed end to end. If 16 such prisms, each of four cubes placed end to end, were piled together, a cube would be produced, and as each of the sixteen prisms would be subjected to the same impact of water which would move it separately, it is apparent that when united into a cube (*b*), the entire mass will be moved as a body, for the area against which the water impinges has been enlarged 16 times. It is of course evident that this holds only for the case here outlined, namely a cube 64 times as large as the original cube. A rock of any other shape would not be moved in the same degree, and as few rock fragments approach a cubical form, the formula can be applied only in a general way. Nevertheless, it is evident that with increase in velocity an enormous increase in carrying power results, and this explains why streams after rains become heavily laden with débris and can perform destructive work of almost unthought-of magnitude, besides carrying away huge amounts of material in a short time and moving along very large blocks of rock.

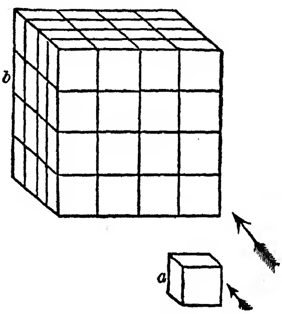


FIG. 380. — Diagrams illustrating the increased carrying power of streams with increased velocity. (After Le Conte.)

In general, a river current flowing at the rate of one fifth of a mile an hour can carry along fine clay; one running at the rate of half a mile an hour transports sand; at the rate of a mile per hour, the current can roll along medium sized gravel; while at ten miles an hour it can roll along pebbles of the size of an egg. There is, however, much variation according to the nature of the bottom, whether covered with sediment or free from it, and whether the finer material is stirred up by eddies, etc., or has to be picked up by the current itself.[1]

[1] For citation of detailed measurements see A. W. Grabau, *Principles of Stratigraphy*, pp. 248–251.

Volume of Material Transported by Rivers. — The total amount of material transported by rivers is surprisingly great, and also varies much for different rivers. Taking some of the large rivers of the earth, we find that the Mississippi, with a flow of 17,500 cubic meters of water per second, carries 211,300,000 cubic meters of material per year; while the La Plata, with a flow of 19,820 cubic meters of water per second, carries only 44,000,000 cubic meters of material per year. Again, the Hoang-Ho or Yellow River of China, with a flow of only 3,285 cubic meters of water per second, carries the enormous quantity of 472,500,000 cubic meters per year, its waters being turbid with sediment. The Mississippi River actually carries more than 400,000,000 tons of sediment into the Gulf of Mexico each year, or more than a million tons a day. The exact volume of material, according to the measurement of Humphreys and Abbot, is 7,471,411,200 cubic feet (211,273,000 cubic meters), a mass sufficient to cover an area of one square mile to a depth of 268 feet. The amount carried to the sea by all the rivers of the earth in one year has been estimated to be about forty times this quantity.

While the coarser material is, as a rule, pushed or rolled along the river-bottom, the sands generally assume the form of low banks alternating in position on the two sides of the stream. They are generally of triangular form, their bases lying against the river bank, and between them and the opposite bank lies the deeper channel with the main current. (See map, Fig. 381, at Delta, and Fig. 605, at Georgetown Bend.) Sand is removed on the upstream and deposited on the downstream side of the sand bank, which thus slowly wanders down stream. This may go on at the rate of 200 to 400 meters per year in some cases (Rhine), and in others (Loire) from less than two meters per day in summer to more than 18 meters per day in winter, which is the season of floods. In all cases the movement of the sands is much slower than that of the water, and the amount of water passing a given point may be a thousand times more than the amount of waste shifted past the same point.

Sorting of Sediments by Rivers

River-transported material is subject to assortment by the destruction of the softer materials in the transport, so that after a while only the most resistant material will remain. A much

FIG. 381. — Flood-plain of the Mississippi River, near Vicksburg, Miss. The highland to the east rises 150 to 250 feet above it. Note, (1) the meandering course; (2) its change since the interstate boundary was fixed; (3) recently abandoned channels: Paw Paw Chute and Old Channel; (4) Wilton Bayou; (5) ox-bow cut-off at De Soto Island; (6) crescent lake: Long Lake; (7) artificial channels: Yazoo River; Diversion Canal and Grant's attempted diversion near Delta; (8) cut banks near Vicksburg; (9) artificial banks or levees near Delta; (10) deposition on inner side of curve south of Delta; (11) "made land" or islands of deposition; (12) concentric ridges and silted hollows near Wilton Bayou, representing lateral migration of the channel; (13) swampy lowland recently abandoned and imperfectly silted. (*Military Geology.*)

worked-over series of river deposits may, indeed, have been subjected so thoroughly to this searching out of destructible material that nothing but quartz pebbles and sand will remain. Observation on Scottish rivers has shown that the percentage of feldspar in the sand derived from the crystalline rocks of the Highlands slowly decreases downstream owing to its progressive destruction. (See p. 415.)

In general, great masses of pure quartz-sand and pebbles, whether unconsolidated or bound together to form a solid rock mass, may be regarded as the product of prolonged and repeated working over by water. While in most cases that work is probably performed by rivers which carry the material a long way, it may also be accomplished by the waves and shore currents of the sea-coast, and in many cases it may be a combination of both.

River Deposits

The deposits of clastic material formed by rivers may be located upon land, in standing bodies of water (lakes, ponds), or in the sea. The last will always be subject to more or less reworking by the ocean waves and currents, which will impress characteristic features upon them. They are, therefore, properly classed as marine sediments. Deposits formed in large lakes also have certain distinctive characters, which require separate treatment. Those deposits, which were built upon the margins of lakes and of the sea, that is, the deltas, are properly considered as special types of river deposits. According to the place and manner of deposition, we may recognize the following types: (1) *Alluvial fans and plains,* (2) *flood plain deposits,* (3) *playas and* (4) *deltas.*

Alluvial Fans and Plains

General Forms and Character. — When a river issues from the mountains, where the slope of its bed is steep and hence its velocity and carrying power great, and descends to the plains or low ground at the foot of the mountains, where as a result of the decrease of slope its velocity and carrying power become suddenly diminished, it is forced to drop a part of the load which it has carried in its mountain course, and in this manner an alluvial fan is built up (Figs. 382 *a* and *b*). This will generally have the form of a low half-cone resting against the high ground in the back, and sloping outward at a low angle in all directions from the point where the river issues (Fig. 382 *b*). The angle of surface slope depends upon

the velocity of the issuing stream, the amount and size of the material which it carries, the size of the fan at any given time, and on other factors. It may be as high as 20° or even 30° in small fans, but in general, the angle is much lower, especially in large fans, where the beds appear nearly horizontal. As the fan grows, the stream breaks up into a number of diverging terminal fringes or *distributaries*, each of which may build a separate lobe of the main fan, whose outer margin will thus become lobate or scalloped. The paths of these distributaries are generally marked by channels cut during seasons when the amount of material brought by the

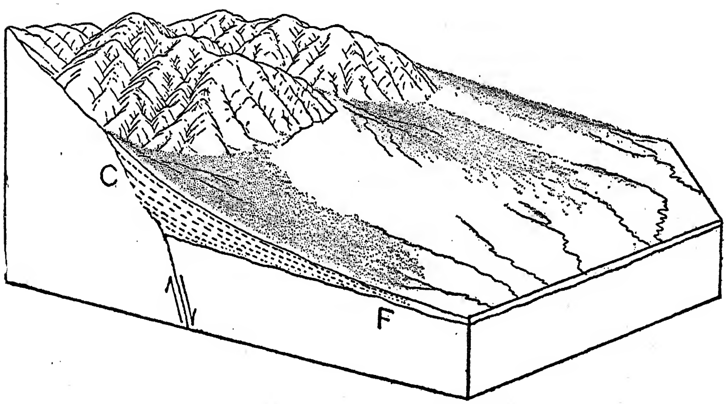


FIG. 382 *a.* — Diagram of alluvial cones, showing surface and underground structures. (Drawn by F. K. Morris.) In this case the original plain, *F*, on which the alluvial cone is built, and the mountainous mass, *C*, are separated by a fault. Note the progressive overlapping of the successive beds of the fan as shown in the section.

stream is smaller and when, therefore, some of the energy of the flowing water-currents is expended in erosion. When several streams issue near together from a mountain region, their separate fans may in time become confluent, forming a more or less continuous deposit along the mountain front. When this is broad and flat it is called an *alluvial plain.*

The area covered by an alluvial fan may vary in size from a few square feet to thousands of square miles, while confluent plains may cover hundreds of thousands of square miles.

Alluvial Fans as Sources of Water. — The steeper alluvial fans at the mountain front commonly furnish a ready supply of water in their deeper layers. This water sinks into the sands near the

head of the fan and slowly makes its way through the sediments. The sloping character of the layers also tends to supply the water with a sufficient "head" to make it available.

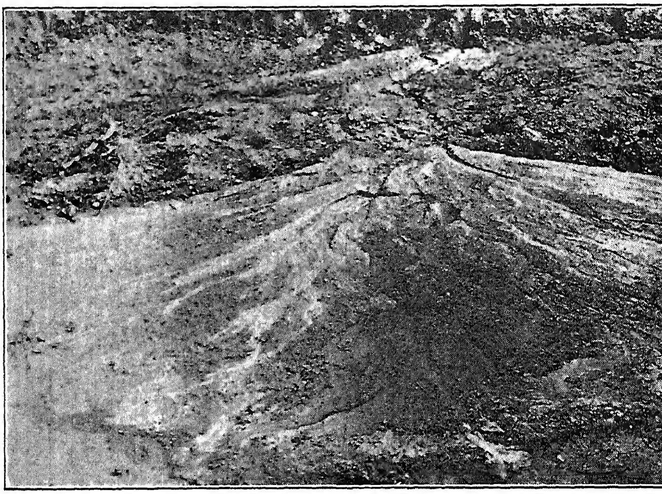


FIG. 382 *b.* — Small alluvial fan, showing distributaries, Utah. (Photo by F. J. Pack.)

Overlaps of the Successive Beds. — As the alluvial fan grows, the upper layers will extend farther than the lower ones, and overlap them around the radius of the fan. Thus in the outer zone of the fan only the highest layers will be present, resting directly upon the old surface upon which the fan is built or upon deposits formed in front of it. As we approach the head of the fan, borings in it would reveal the presence of successively earlier and earlier layers at the bottom. This is illustrated in the following diagram (Fig. 382 *c*),

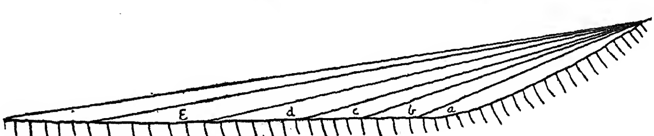


FIG. 382 *c.* — Diagram showing the progressive overlapping of the successive divisions of an alluvial fan, away from the source of supply.

which represents a radial section of such a fan, the oldest layer being lettered *a*, the youngest, *f*.

Modern Examples of Alluvial Fans and Plains

Among the many modern examples of great alluvial fans those of the Merced River of California, the Cooper River of South Australia, the Yellow River (Hoang-Ho) of China, and the Indo-Gangetic Plain may be given.

The Merced River Fan. — The Merced River rises in the Sierra Nevadas and carries a large amount of waste down their western slope. As the river reaches the great open California Valley, which lies between the Sierra Nevadas and the Coast Ranges, it drops its material and builds an alluvial fan, which has at present reached a radius of about 40 miles. The material of this fan consists of coarse gravel near the mountains, and of fine silt in its outer portion. The slope of the fan, on the whole, is a very gentle one, on account of which the river is easily diverted at the point of issuance, and may follow different directions across the fan at different times.

The Merced fan is only one of a number of such fans built by the rivers which flow from the Sierra Nevadas into the Great Valley. These fans are so large, their slopes so low, and their confluence so complete, that it is difficult to recognize the individual convexity of each without the aid of surveying instruments. Similar, though smaller, fans descend from the eastern slopes of the Coast Range which bounds the valley on the west, and these two sets meet in the center of the valley to form a broad, flat-floored trough.

The Delta of the Cooper River, Australia. — The Cooper River is one of the many intermittent streams which rise in the mountains of Queensland and flow westward to the lake district of South Australia during seasons of flood. It enters Lake Eyre, a saline body of water 12 meters below sea-level. This river has built a delta or alluvial plain of large size, but as it is not built in a permanent body of standing water, its character lies midway between that of an alluvial fan and a true delta. The area of this delta-plain is more than twice that of the Nile Delta, its length being nearly 185 miles and its width over 170 miles. The surface of the delta-plain is dissected by numerous dry channels through which the water flows after periods of rain.

Alluvial Plain of the Hoang-Ho. — The Hoang-Ho or Yellow River of China leaves the mountains at a point about 300 miles from the present sea-shore, and over this distance it has built a very gently sloping alluvial plain, which spreads out in the form of a triangle, the base of which, along the present coast, extends for about 400 miles south from Pekin to the great plain of the Yangtze-Kiang, including and surrounding the rocky headland of Shantung. The head of the plain, where the river leaves the mountains, is only 400 feet above sea-level, hence there is only an average fall of $1\frac{1}{3}$ feet per mile, making a surface of such gentle slope that it appears in all respects horizontal (Fig. 383). This very gentle slope is due to the fact that the material of which this plain is built is mostly fine silt derived from the loess of the interior. It is the yellowish color of this material, due to the hydrated iron in it, which has given the Yellow River its name (see *ante*, p. 459). This fine material is deposited in a series of nearly horizontal layers, one above the other, forming thus a regular succession of beds or *strata*, and giving the deposits a regular *stratified* character.

Because of the gentle slope, the river is easily diverted from its course when swollen, and a slight change at the head may produce a marked alteration of

the distributing streams over the surface. The main mouth of the stream has been repeatedly shifted, the extent being as much as 200 miles. The plain is intensively cultivated, and there are many lakes, ponds, and swamps in which vegetable deposits accumulate, forming peat beds, which in time may be converted into coal. When the river breaks its banks, inundations of vast extent result, and such deposits of peat become buried by the silt. In 1887 such a flood covered an estimated area of 50,000 square miles of immensely fertile

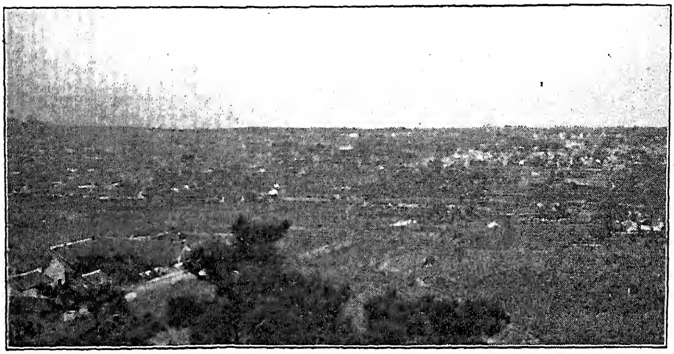


FIG. 383. — View of the flat alluvial plain of the Hoang-Ho in eastern China.

and densely inhabited land. At least a million people were drowned, and an even greater number succumbed to the famine and diseases which resulted because of the flood.

The Indo-Gangetic Plain. — The streams descending from the southern slopes of the Himalaya Mountains in northern India, and the ranges extending westward, carry large quantities of clastic material produced by the disintegration of the rocks during the dry season of the year and their decomposition during the moist season (Fig. 384). Along the foot of the mountains numerous alluvial fans of coarse material and steep grade are built, while the finer material, carried forward into the lowland of northern India, becomes incorporated in the great alluvial plain which is traversed by the two major streams of north India, the Ganges, with its tributary the Brahmaputra on the east, and the Indus on the west. This Indo-Gangetic Plain, as it is called, has an area of about 300,000 square miles, varying in width from 90 to nearly 300 miles. It entirely separates the lower peninsula of India from the Himalayas on the north, and forms the richest and most densely populated district of India. The highest portion of this plain rises only 924 feet above the sea-level, the average slope of the surface being of similar degree to that of the Hoang-Ho plain (Fig. 385). Borings into this plain, which have penetrated to nearly 1000 feet below sea-level, have shown that the material is essentially the same throughout. This means, of course, that the region is sinking as the deposits are being formed, otherwise the beds now a thousand feet below the sea could not have been formed above that level as are the modern beds, which these older ones resemble in all respects. This belt of country parallel to the Himalayas thus constitutes a modern example of a *geosyncline of deposition*, a structural feature of the earth's crust to which we shall refer again in subsequent pages.

The material of which this great deposit is composed varies greatly in character. Along the sloping borders, especially in the north, gravels are common, but away from these, fine material prevails, pebbles being scarce at a distance of more than 20 or 30 miles from the hills. This finer material consists of sands more or less well assorted, of clays, and of other substances. Beds of wind-blown or eolian sand of great thickness are found in some regions. In some sections the shells of river and pond mollusks are common in the clays, and in other sections, as along the banks of the Jumna River, the bones of many land and river animals are embedded in the sediments, among these being the remains of elephant, hippopotamus, ox, horse, antelope, crocodile, and various

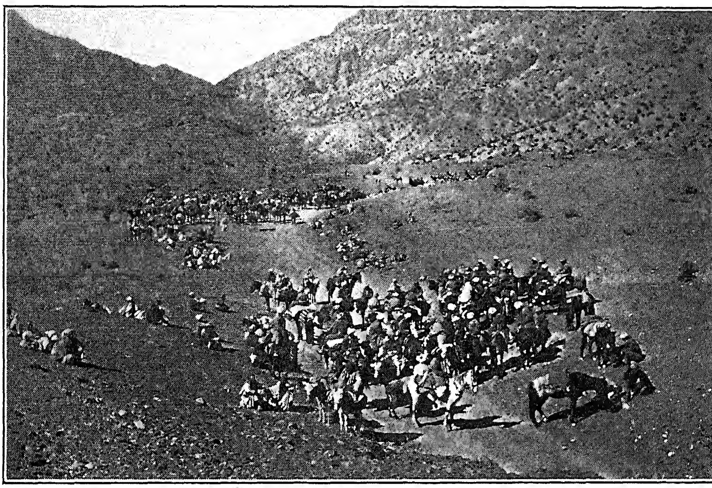


FIG. 384. — Khyber Pass in the Himalayas, showing the extensive formation of rock-waste.

fish. Peat beds are also forming in many sections, and older peat beds, buried by later sediments, have been found at a depth of 20 to 30 feet below the surface in the borings. Bones of terrestrial mammals and crocodiles, etc., have been found at considerable depths, but nowhere are there any traces of marine organisms, showing that throughout the period of deposition of these sediments the region stood sufficiently above sea-level to prevent marine waters from entering.

At various levels beds of earthy limestones or layers of calcareous concretions, called *kankar*, are found, these representing the lime which was separated out from the river-water under the semi-tropical heat of the sun (see *ante*, p. 260). Such lime, derived from the solution of older limestones in the upper river courses, is not uncommonly deposited in regions of semi-aridity in various parts of the world.

On the eastern side of the plain, where the Ganges enters the sea, it builds a normal delta, and here some of the beds enclose the remains of marine organisms. Similar conditions exist upon the western side, where, moreover, extensive sea-

border marshes and salt-pans exist, and where salt deposits are included in the series of stratified sediments which are forming there (*ante*, p. 233). Salt lakes and playas also exist inland, where climatic conditions are favorable for the evaporation of salt-bearing waters.

The thickness of the deposits of the Indo-Gangetic Plain is not known, but it probably exceeds several thousand feet. It rests in part upon an older deposit of precisely the same character, a portion of which, near the mountains, has been bent or tilted by a comparatively recent uplift or rising of the Himalayas. These uplifted ends have been more or less dissected by the modern streams, so that the character of the deposits is ascertainable. Thus it is seen that the material of this older alluvial plain is similar to that which forms the

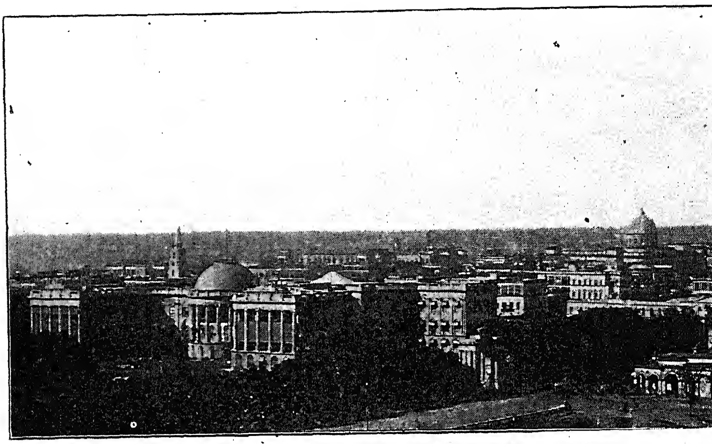


FIG. 385. — Flood-plain of the Ganges; from Calcutta.

modern plain, and like it includes the remains of land and fresh-water animals. The remains of marine organisms are found only in its lowest portion, where it grades into the underlying marine formation. The most surprising thing about this older alluvial fan deposit is its enormous thickness, which is in the neighborhood of 15,000 feet. As the material of this fan was laid down at a comparatively slight elevation above the sea, — judging from what is seen in the deposits now forming, — it is apparent that during its formation there must have been a slow but constant sinking of the area over which it was deposited, and that when the topmost layer was spread out, the bottom layers must have been more than ten thousand feet below sea-level, from which position they were lifted by the subsequent disturbance which affected this region.

Another striking feature of this older deposit is the presence in it of beds of red clay, often of great thickness. These red beds were originally deposits of yellow sandy clays such as now form upon the modern plain. The yellow color is due to the oxidation and hydration of finely disseminated iron in the sediments, the thorough oxidation of which is accomplished whenever, during the dry seasons, the ground-water level sinks so low that air can penetrate and to some extent circulate through the sediments. The red color of the older deposit is

merely a later stage in change, the iron losing its water with age, and so changing to the red oxide (hematite), just as the burning of bricks from yellow clay drives off the combined water of the iron and changes the color from yellow to red.

Deposits in Mountain-enclosed Basins

Where a basin lies within the mountains with only a single outlet or with none at all, clastic material formed by weathering on the mountain sides will be washed by the rivers into the center of the basin where it accumulates, often to a very great thickness. If the climate is moist, the basin will be filled with water to the point of overflow, forming a lake or series of lakes, while the amount of clastic material washed into this basin will be comparatively small, because weathering will be interfered with by the cover of vegetation which forms upon the mountain sides. Thus the clastic deposits formed on the floors of the glens and other valleys in the Scottish Highlands are never very extensive, though peat deposits form on all the mountain sides and on the valley bottoms as well. In regions of dry climate, however, where vegetation is scant or absent at least for parts of the year, much weathering results, and the product of such weathering accumulates upon the floor of the intermontane basin. A typical example of such a waste-filled basin is the Vale of Kashmir, which lies within the northwestern ranges of the Himalaya Mountains. Its area equals that of the Connecticut Valley of the eastern United States, being of elliptical form, 100 miles long from southeast to northwest, and 40 or 50 miles broad. The floor of the valley is more than 5000 feet above sea-level, and it is deeply filled with waste material from the mountain sides, this material being coarse around the margins, but fine toward the center, where it is free from pebbles. Its thickness is probably several thousand feet, though no borings have been made to determine this. The waters of the various streams which bring the material from the mountains and deposit it upon the valley floor are gathered to form the Jehlam River, which meanders across the plain and escapes from the basin by a deep and rocky gorge.

A similar waste-filled basin exists in the Rocky Mountains in the upper valley of the Arkansas River, which escapes from the basin by the Royal Gorge. The deposits within this basin slope from the mountains toward the river borders.

Deposits formed at an earlier period (Tertiary) in a similar basin in southwestern Wyoming, which is enclosed by the Wasatch, Uinta, and Wind River

ranges of mountains, have now been thoroughly dissected, apparently as the result of a change in climate, which brought with it increased precipitation of moisture. This dissection is accomplished by the Green River and its tribu-

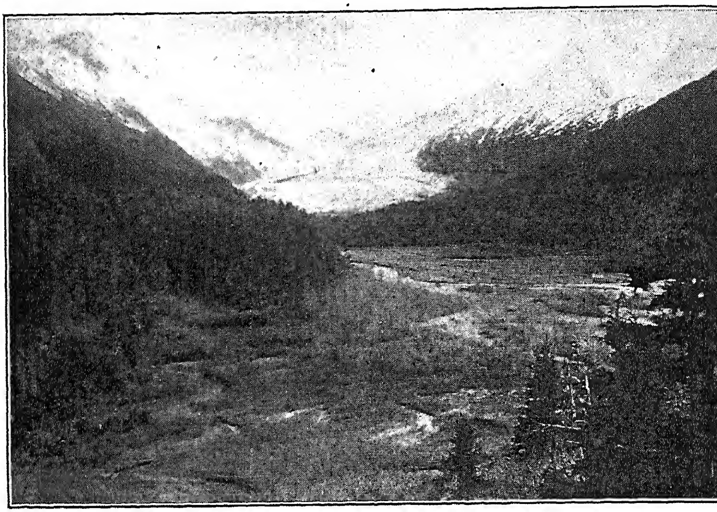


FIG. 386. — Flood-plain of the river escaping from the front of the Bartlett Glacier, Alaska. (Courtesy of Alaska Engineering Commission.)

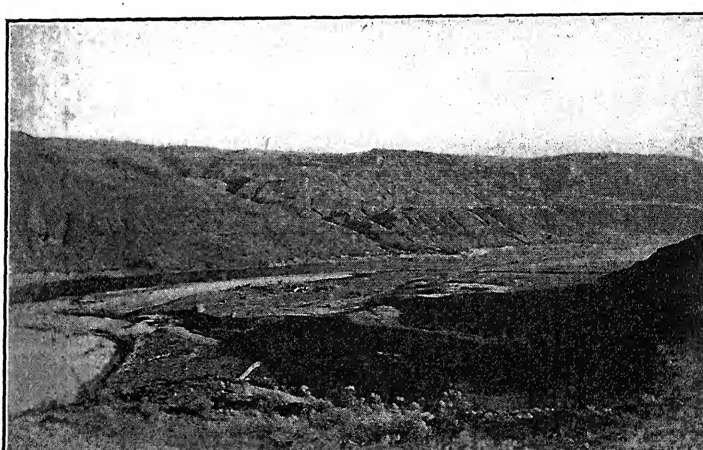


FIG. 387 *a*. — Morainal and river terraces on east side of Columbia Gorge, Chelan Ferry, Wash. (Photo by Baily Willis, from U. S. G. S.)

taries, the waters of which escape by a deep gorge through the Uinta Mountains. As a result of this dissection the older parts of the deposit have been laid open to view, in cliffs sometimes a thousand feet high, and the details of structure

and composition of such deposits can thus be studied to great advantage, whereas those of the undissected deposits can be ascertained only by borings.

River Flood-plain Deposits

When a river is heavily laden with sediment, it is bound to deposit this wherever, by an expansion of its bed or a lessening of its grade, the velocity is decreased. A river escaping from the foot of a glacier usually carries a large quantity of fragmental material, both coarse and fine, and the former is deposited soon after the river leaves the ice front (Fig. 386). During the last glacial period, when vast ice masses covered much of northern North America and northwestern Europe, the rivers escaping from the front of this ice, during periods of prolonged melting, carried large quantities of coarse débris and deposited this in their valleys, often filling them from side to side to a depth of even a hundred feet or more. Subsequently when, owing to the melting away of the ice, less débris was furnished, the energy of the river was expended in again cutting away the old deposit. Commonly, however, the deposit was not completely removed, but terraces of the old sedi-

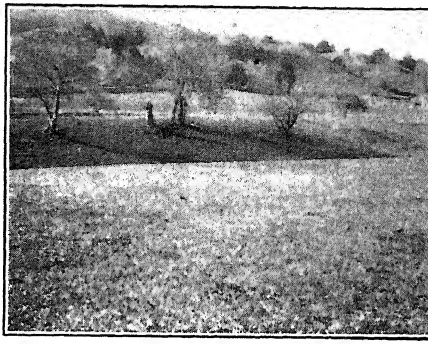


FIG. 387 *b*. — Old terraces of the West River, Brattleboro, Vt. (Photo by Prof. E. Fisher.)

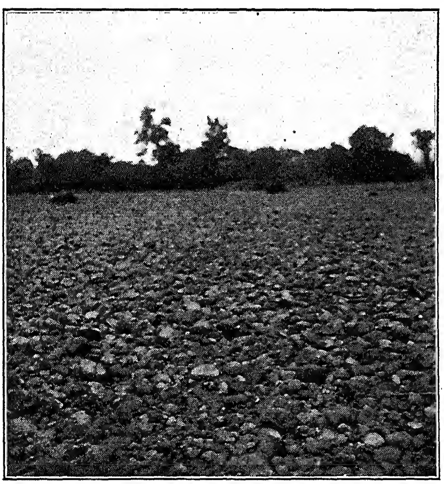


FIG. 388 *a*. — Flood-plain of the Saco River at Intervale, N. H., showing the coarse material derived from an erosion of the terraces. (Photo by the author.)

ment were left on both sides of the river valley. Such terraces may be seen along most of the larger streams in the northern

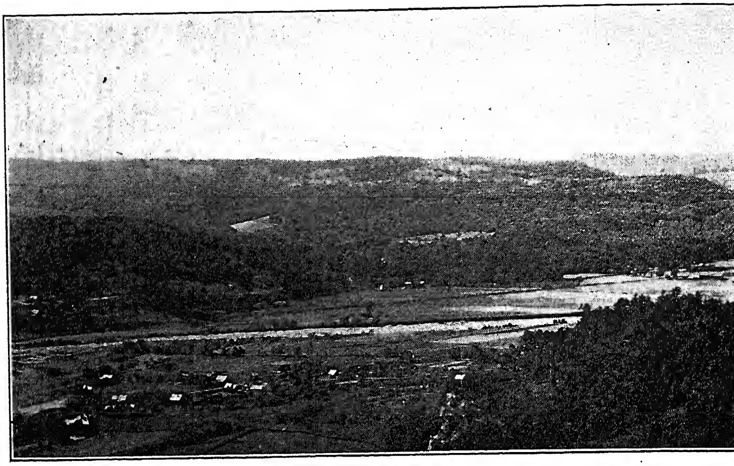


Fig. 388 *b*. — Flood-plain of Connecticut River, in Vermont.

states, often occurring in several successive series, each lower than the preceding, and each set marking, by its summit level, which is in accord on opposite sides of the valley, a temporary surface of

Fig. 389. — The Ohio River in flood, showing inundation of flood-plain.

the flood-plain of the river before it resumed cutting toward a lower level (Figs. 387 *a*, *b*). Close to the front of the old ice sheet the material of which these terraces are composed is very coarse, boulders and cobblestones of the size of a man's fist often pre-

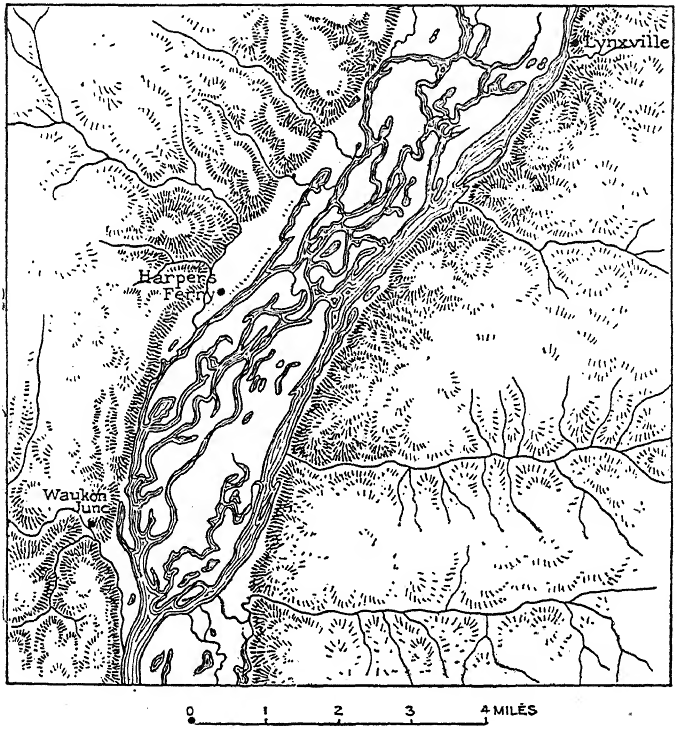


Fig. 390 *a*. — A well-developed river flat, Mississippi Valley, near Prairie du Chien, Wis. Note the steep confining bluffs and numerous lagoons, crescent lakes, ox-bows, cut-offs, and abandoned channels, showing various stages of silting. (From *Military Geology*.)

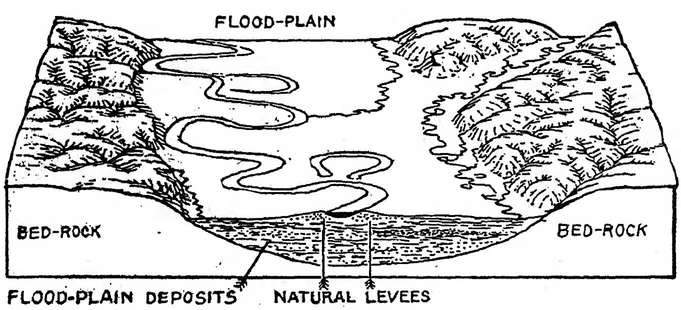


Fig. 390 *b*. — Block diagram showing the flood-plain of a river, with ox-bows and marginal streams; and, in section, the flood-plain deposits and natural levees. (Drawn by F. K. Morris.)

dominating (Fig. 388 *a*). Farther down stream the material becomes largely sand, increasing in fineness with its distance from the original source.

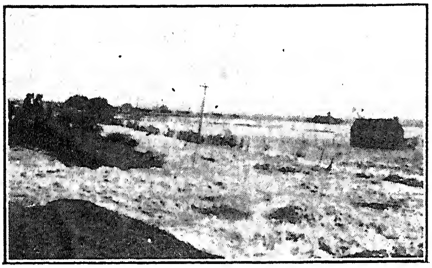


Fig. 391. — Break in levee of the Mississippi River opposite New Orleans, submerging a plantation. (Photo by Howell.)

Where rivers flow at a gentle grade, as in the case of the lower reaches of most large rivers (Fig. 388 *b*), the flood-plain, which is that part of the valley floor inundated only at high water (Fig. 389), is very commonly made up of layers of fine mud, with many ponds and swamps scattered over its surface (Fig. 390 *a*). The mud is derived from the river, which, on rising, overflows its banks. If

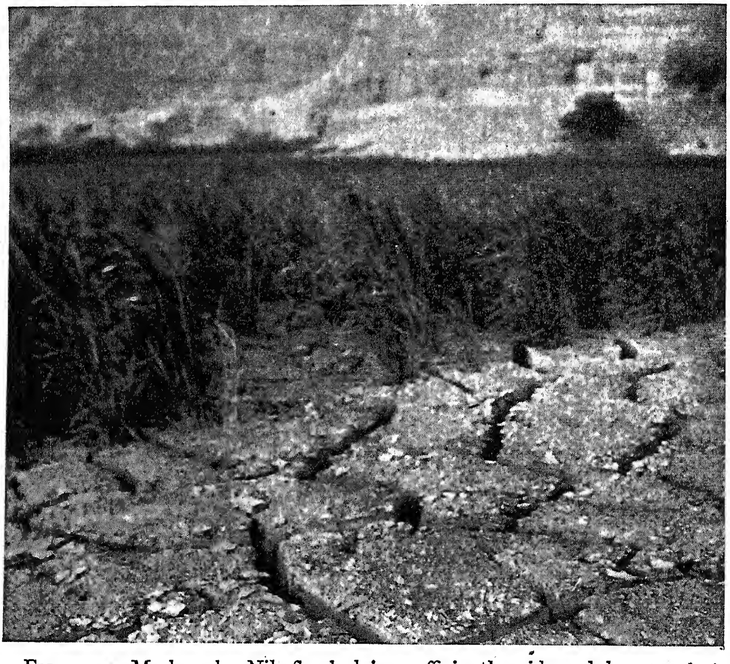


Fig. 392. — Mud cracks, Nile flood-plain; sufficiently wide and deep to admit a man's arm to the elbow. Abu Simbel, near second Nile Cataract. (After Hobbs. Courtesy of the American Geographical Society, Broadway, at 152d St. From the *Geographical Review*.)

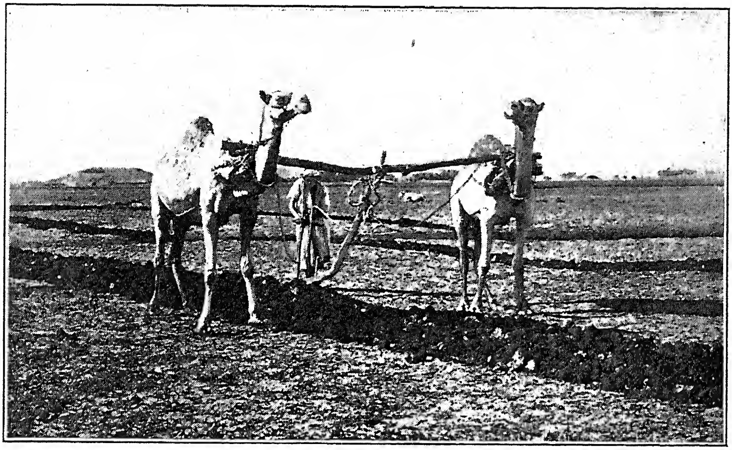


FIG. 393. — The flood-plain of the Nile. Plowing with the aid of camels.

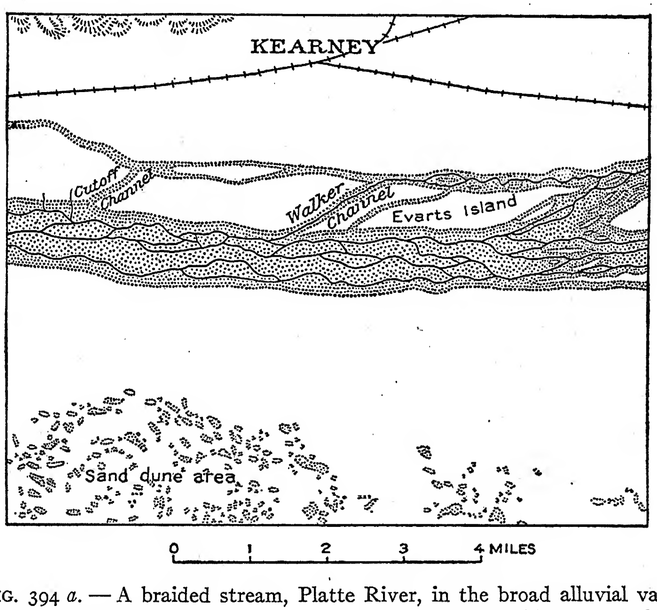


FIG. 394 *a*. — A braided stream, Platte River, in the broad alluvial valley near Kearney, Neb. A mile-wide, sandy channel filled with water only at flood time. Over the bottom during most of the year a little water, not diverted for irrigation, percolates through the sand, or finds its way in a tortuous course through a series of interlacing channels whose pattern changes with every flood. Northwest winds here lift the sand from the channel, sweep it across a grassy plain, and pile it in dunes nearly two miles south of the river. (Kearney, Neb., topographic sheet, U. S. G. S. From *Military Geology*.)

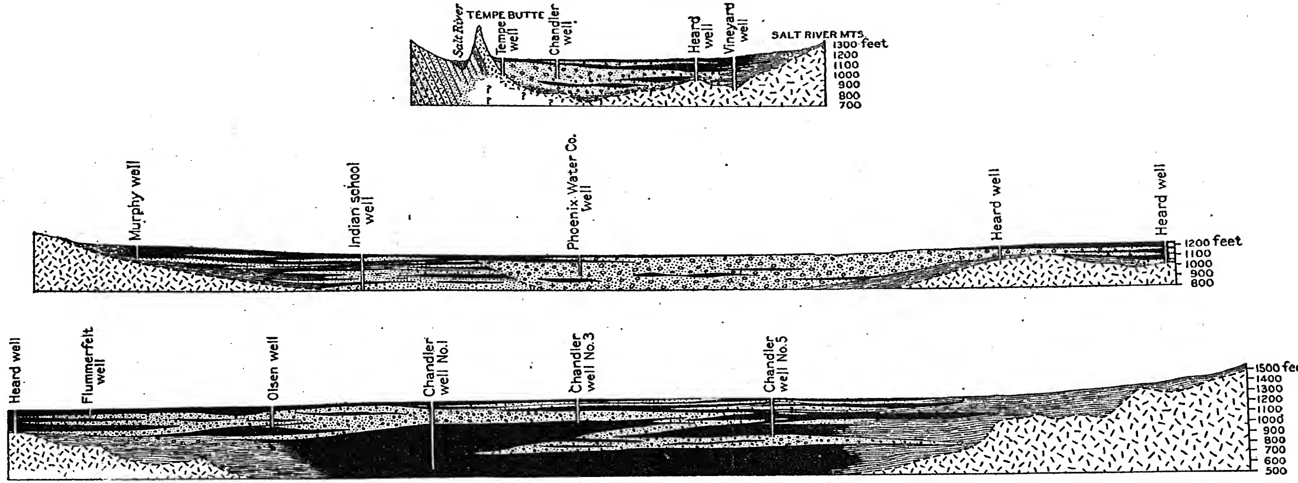


FIG. 394 *b*. — Work of Salt River, Arizona. The profile showing the character of the valley-filling as interpreted from well borings. From the "underground river" which flows through coarse gravel, water enough is pumped to irrigate several thousand acres of land. (After W. T. Lee. U. S. G. S.)

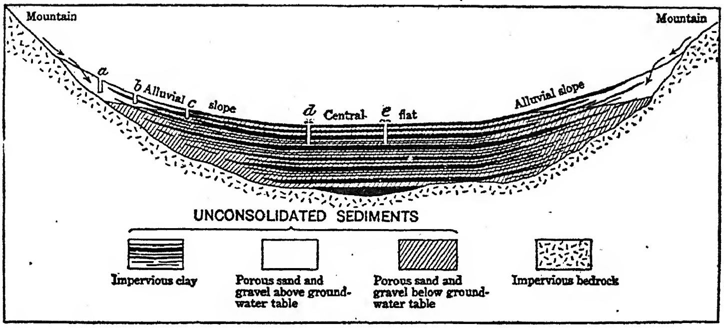


FIG. 394 *c*. — Diagrammatic section showing artesian conditions in Sulphur Spring Valley. *a*, dry hole, which if sunk deeper would strike rock without finding water; *b*, dry hole which if sunk deeper would find water; *c*, shallow pump well; *d* and *e*, flowing wells. (*Military Geology.*)

vegetation grows along the bank, this will commonly retard the current of the spreading river, and as a result, a considerable amount of the river silt will settle out along its banks, building up natural levees. Such natural levees are very characteristic of the Mississippi and other large rivers (Figs. 390 *b*, 391). Beyond them the country is generally lower and swampy, with many lakes, as in the "Back Swamps" of the lower Mississippi (see map, Fig. 381, p. 463). Because the mud settles out in relatively small quantities at each flooding, the layers composing the flood-plain will, as a rule, be thin, and a finely stratified structure results. As the mud dries after a flooding, it breaks into polygonal blocks separated by cracks, the depth of which depends on the length of exposure and on other causes. Such sun-cracked

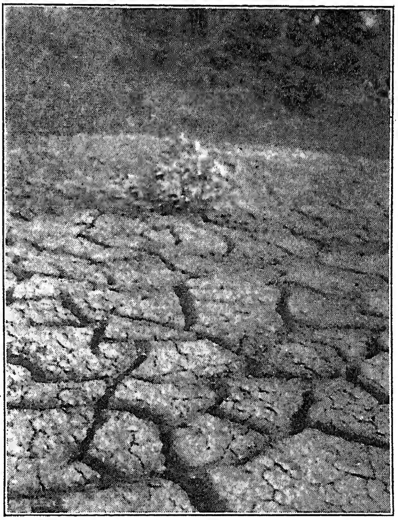


FIG. 395. — Mud-cracked surface on bank of Little Colorado River, Texas, formed during drought of 1918. Some of the large cracks are from 4 to 10 inches deep, and a secondary set of finer ones has formed upon the larger blocks. (Photographed and contributed by Prof. Elizabeth Fisher, Wellesley College.)

or "mud-crack" surfaces are very characteristic of river flood-plains (Fig. 392). Illustrations of mud-cracks from the flood and delta-plains of American rivers are given in figures 395 and 396.

The flood-plain of the Nile (Fig. 393) extends for a length of 500 miles and has a width ranging from five to fifteen miles, which on the delta increases to 100 miles. On both sides it is bordered by rocks or by desert sands, while the banks at low-water are from 20 to 30 feet in height. The river overflows its banks every year, the flood beginning in June and usually rising 25 feet or more

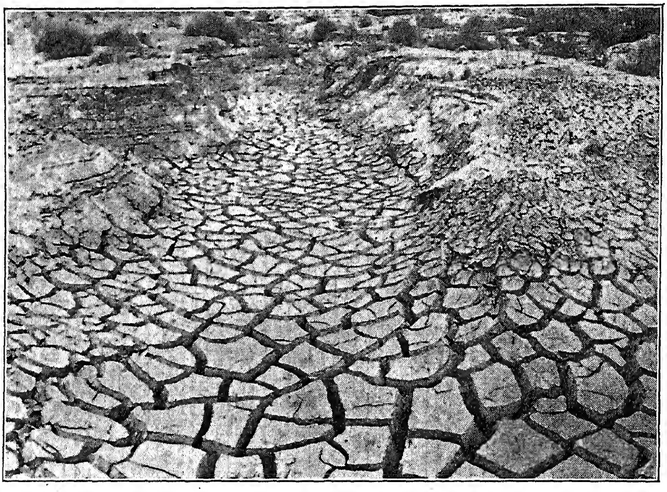


FIG. 396. — Mud-cracks on the delta of the Colorado River. (Photo by G. K. Gilbert, from U. S. G. S.)

at Cairo in the late summer or early autumn. The annual addition of the river silt causes a slow rising of the flood-plain at a rate estimated to equal 4½ inches in a century.

Flood-plains of rivers of variable flow, where a large amount of material is brought from the mountains during flood time, while little or no water occupies the channel during the dry season, have special surface characters and structure. The excessive amount of silt causes the river to break up into a series of interlacing threads, forming a "braided" structure (Fig. 394 *a*). The deposits themselves consist of variable and discontinuous layers of interfingering coarse and fine material (Fig. 394 *b*, *c*).

Playa Deposits

When rivers end in desert basins from which there is no outlet, they form saline or more rarely fresh lakes (Fig. 397) or they spread out after a period of flood into flat and very shallow *playa lakes* which disappear again by evaporation. Such playa lakes come into existence very suddenly on account of the usual flat

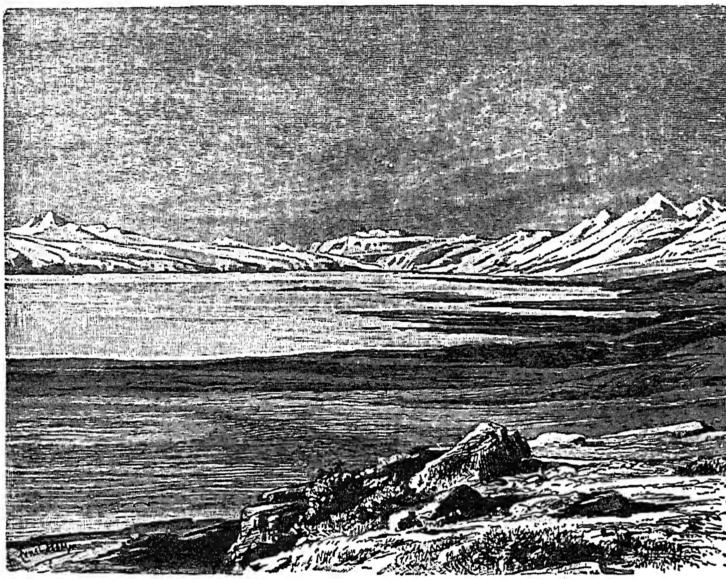


FIG. 397.—Lake Sorkul, without outlet, in Great Pamir Desert. (After Reclus.)

bottom of the basin, and they are often of considerable size. In the Black Rock desert of Nevada a large playa lake forms every winter, covering an area of 450 to 500 square miles, but seldom reaching a depth exceeding a few inches. An Old World playa lake has been known to become full grown in twenty minutes, reaching a width of 10 to 15 km. and an unascertained length, with a depth ranging only from one to six inches. Often such a playa lake is only a body of very liquid mud, and as the water dries away this mud settles down as a continuous but thin sheet over the entire bottom. In a few hours or a few days the water has evaporated, leaving a hard, dry, and absolutely barren playa surface, cracked in all directions as the mud contracts in drying. When the river water carries salts

in solution, these remain behind on evaporation of the lake water, either impregnating the muds or forming distinct layers. Besides the mud cracks and occasional impressions of raindrops left by a passing sharp shower, the footprints of many animals which come to these waters to drink may be impressed upon the mud surface and retained in it on drying. If, subsequently, sands are blown across such a surface or washed there by a later inundation, they will not only fill the cracks between the polygonal blocks, into which the surface has been broken while drying, but will also cover, and preserve a relief impression of, the raindrops and foot-prints. On solidifying, the resulting layer of sandstone will have such relief features on its under side, while the hardened mud retains the actual impressions. In the sandstones of Triassic age found in eastern North America and in Europe, many such relief impressions of footprints of now extinct gigantic land reptiles (Dinosaurs) and of Stegocephalians (Fig. 398) are found (see Chapter XLIV). The actual impressions are also present in the mud-rock beneath, but these are not easily obtained on account of the readiness with which the mud layers shatter on quarrying. Trails of insects and other organisms are also formed upon the playa surfaces, and sometimes these are preserved; but the actual remains of animals are seldom found, since those that die are rarely buried by the sands and muds before their bones have completely disintegrated.

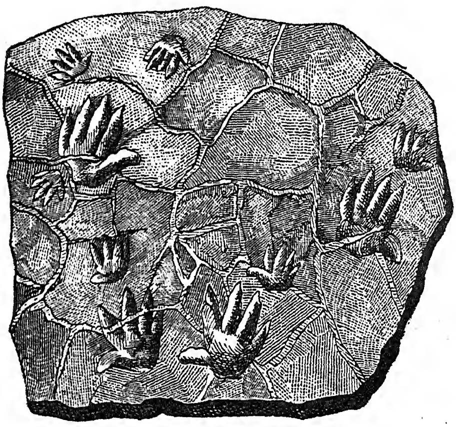


Fig. 398. — Tracks (in relief) of Chirotherium, Buntsandstein, Hessberg, Germany. (From Haas' *Leitfossilien*.) This slab represents the consolidated sand which was spread over the original surface on which the foot-print impressions were formed. The relief structures here shown are, therefore, the natural "casts" of the original impressions and represent the form of the animal's feet. The side with these relief structures is the under side of the slab.

Playa lakes which endure for some months may become stocked

with animals whose eggs can withstand prolonged periodic drying, and develop only when the lake comes into existence. Originally such eggs may be brought by the wind or by birds or otherwise, but few long-existing lakes are without them unless their water is very salty. Chief among such forms are the small fresh-water crustaceans of the genera *Estheria*, *Cypris*, etc. (Fig. 399), the shells of which may cover the playa surface in considerable number

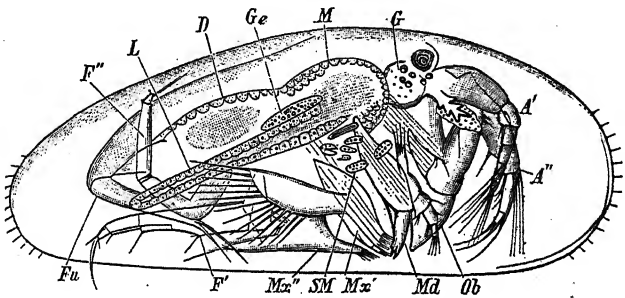


FIG. 399. — *Cypris*, a modern ostracod. Female before sexual maturity, right valve of shell removed to show internal anatomy. *A'A"*, first and second pair of antennæ; *Ob*, upper lip; *Md*, mandible with leg-like feelers; *G*, cerebral ganglion with impaired eye; *Sm*, shell muscle; *Mx'*, *Mx"*, first and second pair of maxillæ; *F'*, foot for crawling; *F"*, foot for cleaning; *Fu*, furka; *M*, stomach; *D*, intestine; *L*, liver; *Ge*, genitals. Much enlarged. (From Haas.)

after drying, and may even form thin deposits mostly composed of such shells. *Estheria* is known to live in playa ponds which are dry for eleven months in the year. Forms of this type are also found in some of the mud layers in the Triassic series of sediments referred to above. River fish, too, may be swept in large numbers into such temporary lakes, and their remains may become buried in the accumulating deposits.

On the whole, playa deposits have many characters in common with the mud deposits formed on river flood-plains, and ancient deposits of one type may easily be mistaken for those of the other.

Deltas

Where rivers laden with sediments enter a lake or the sea, they will build a normal delta, provided the shore currents are of insufficient strength to remove all the material brought by the rivers. Because of the absence of tides in lakes, the deltas built into such water bodies will be more perfect and less variable than those built

into the sea. The name delta is derived from the resemblance of one of the best-known examples, the delta of the Nile, to the Greek letter delta (Δ), though few deltas have such a regular triangular

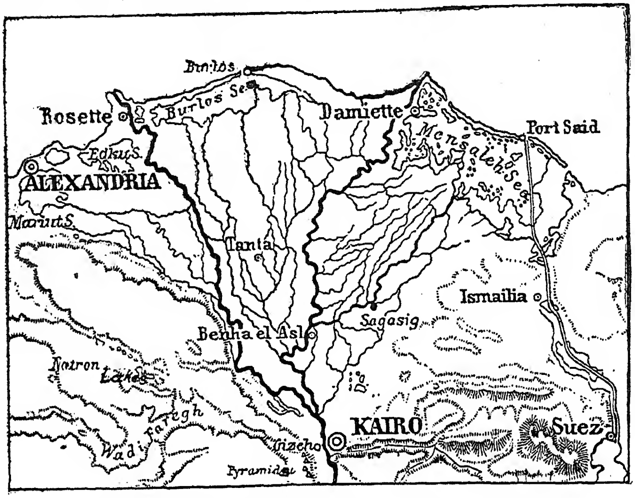


FIG. 400. — Map of the Nile Delta. (After Kayser.)

form (Fig. 400). Small deltas, especially those built in lakes, show two sets of beds, one sloping lakewards at a considerable angle (up to 20 degrees or more) and generally composed of the finer material, and one set which is nearly horizontal or but slightly

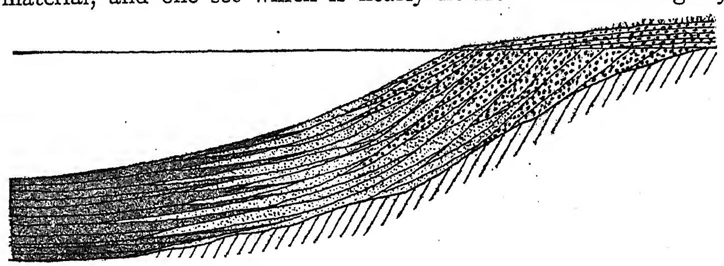


FIG. 401. — Section of a small delta in a lake, showing the foresets of pebbles and sand, the bottom-sets of clay, and the topsets of coarse sand and pebbles. (After Kayser.)

inclined, and is generally composed of coarser material and rests upon the steeper beds with an abrupt change of angle. The first series is called the "foresets," the second the "topsets" (Figs. 401, 402). Deltas built in the sea are of more complicated structure, though in general the two sets of beds may also be recognized.

On the surfaces of large deltas, such as those of the Nile and the Mississippi, many ponds and more or less permanent lakes may exist. Most of these will be fresh-water lakes, but along the seacoast salt-water lagoons and shallow lakes will often be found. If the climate is dry, some of these shallow lagoons may become natural salt pans, as is the case with some of them along the edge of the Nile delta. The main stream, too, commonly divides into many ramifying branches or *distributaries*, which intersect the sur-

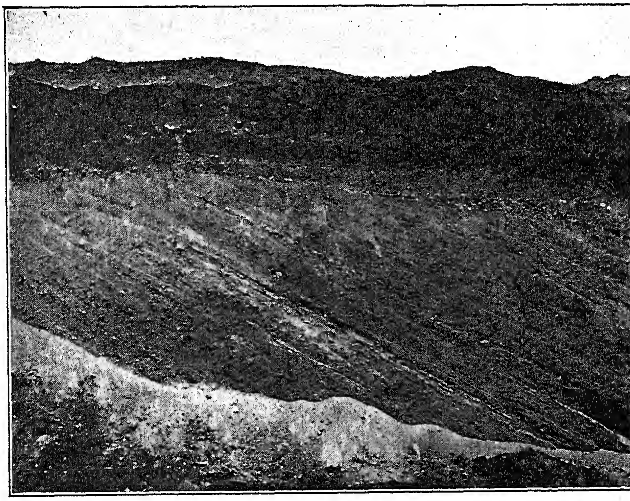


FIG. 402. — Section of a delta-plain built into Lake Bonneville, Utah. The finer-grained inclined foreset beds are covered by horizontal and coarser topset beds. (Photo by F. J. Pack.)

face of the delta, and some of these streams may build independent lobes or even long arms into the sea, as is the case in the " bird-foot delta " of the Mississippi (Fig. 403).

The muds of the delta are very apt to bury and preserve the remains of fish and other animals which live in the rivers or in the ponds upon the delta surface, and if the river comes from wooded regions, tree trunks and branches may also be buried. The vegetation, too, which grows upon the surface of the delta and in the ponds will leave its remains in the deposits. Along the sea margin, marine animals, especially floating types and seaweeds, may be cast upon the delta surface during storms, or may become stranded after a temporary flooding of the delta by the sea-water. Lakes or ponds near the coast may also receive such organisms by overwash

from the sea. Thus a commingling of the remains of river, pond, and marine organisms is to be expected along the borders of the delta. (For illustrations of the common forms see *ante*, pp. 310 to 316.)

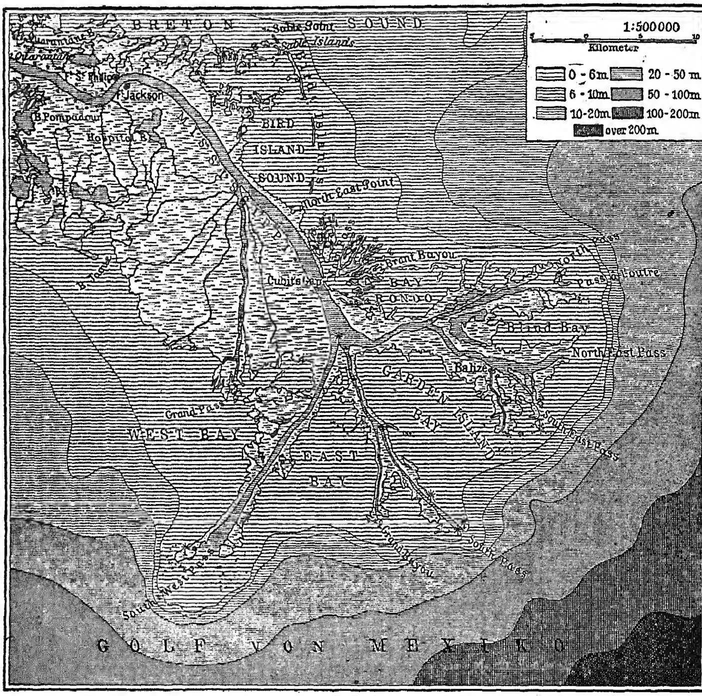


FIG. 403. — Bird-foot delta of the Mississippi. (After coast survey chart.) The various shades show the depths of water in meters as indicated in the legend. (From Ratzel, *Die Erde.*)

Structural and Other Physical Characters of River Deposits

Among the important structural characters found in most river deposits, the following may be mentioned: (*a*) stratification, (*b*) cross-bedding, (*c*) cut-and-fill structures, (*d*) ripple marks, (*e*) rill-marks, (*f*) mud-cracks, (*g*) raindrop impressions, (*h*) footprints, (*i*) clay galls, etc. It must be clearly understood, however, that these structures are not confined to river deposits, though special phases of them may be so restricted.

Stratification (Fig. 404). — This is the arrangement of rocks in layers, each of which was at one time the topmost one. The individual layers or beds are called the *strata* (singular, *stratum*), especially if they differ markedly in character, as, for example, a stratum of clay which is followed by a stratum of sand or by one of peat. Within each stratum there may be minor layers or *laminæ*

which vary slightly in texture or color or other characteristics. The strata of river-laid deposits vary with the coarseness and character of the material (Fig. 394 *b*, p. 478). Coarse deposits, such as pebbles, are often very irregular, varying from thick to thin, and often passing laterally into sands. Even the strata of sand are not always regular, but vary in thickness, and often thin away or pinch out. Such variation is readily seen when two sections, a short distance apart, are compared (Fig. 405). The fine deposits, on the other hand, such as characterize the flood-plains and playas, are commonly well stratified, regular, and occur in layers of uniform thickness over wide areas and generally show a finely

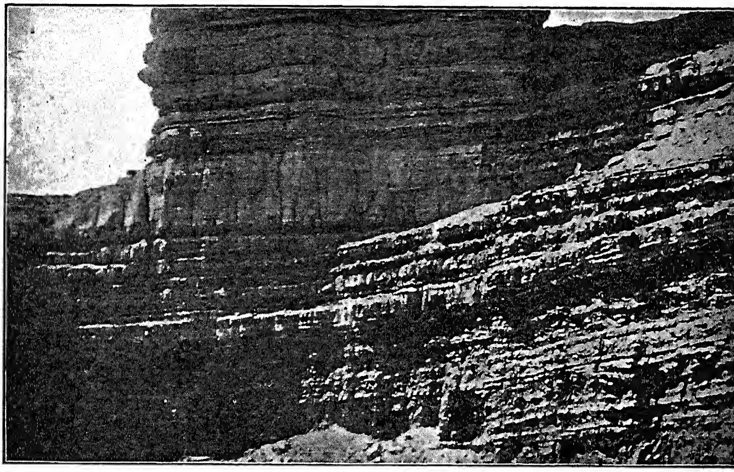


FIG. 404. — Cliff cut on horizontal well-stratified rocks. Note the heavy *stratum* near the center. Weathering of weaker strata has left the harder ones projecting and this has emphasized the stratified appearance.

laminated structure. In this respect, they are as well stratified as are marine deposits. (Compare Fig. 16, p. 81, and Fig. 487, p. 579, the former an ancient marine, the latter a flood-plain deposit of the same age.)

Cross-bedding. — This structure is well marked in river deposits which are formed by more or less torrential currents that carry forward a large amount of material at a time. Consequently it is best developed in the coarser-grained deposits, such as sands and the finer pebble beds. Typically it is characterized by a succession of sloping layers separated by horizontal beds. The parts characterized by the sloping layers may be as much as four or five feet in thickness, the angle of slope of the layers being from 20 to 30 degrees. At the bottom these layers tend to change toward horizontality, but at the top they are generally abruptly truncated, and a set of horizontal beds up to several feet in thickness rests upon their edges. Above these horizontal layers is a second series of sloping beds, similar to the first and with the inclination in the same direction. There may be many such successions of sloping and horizontal beds, but in all cases the inclined beds dip in the same direction, which is that of the flow of the current. Such a type of cross-bedding is readily

distinguished from the eolian type, in which the slopes are in varying directions and the successive divisions are separated by erosion planes instead of horizontal layers. The following diagram (Fig. 406) illustrates this type of cross-bedding, which may be taken as indicating deposition by torrential rivers whenever found. An irregular form of cross-bedding is also produced by rivers where there is a confluence of opposing currents. Lyell described the structure of a sand bank formed in the spring of 1828, where the opposing currents of the Rhone and the Arve met and neutralized each other, causing a retardation of their motion. Into this sand bank a section was subsequently cut, which is reproduced in the following figure (Fig. 407). This section was about twelve feet long and five feet high. The stratum AA consists of irregular alternations of pebbles and sand in undulating beds; below these are seams of very fine sand, BB, some as thin as paper, others about a quarter of an inch thick. The stratum CC is composed of layers of fine, greenish gray sand as thin as paper. Some of the inclined beds will be seen to be thicker at their upper, others at their lower, extremity, the inclination of some being very considerable.

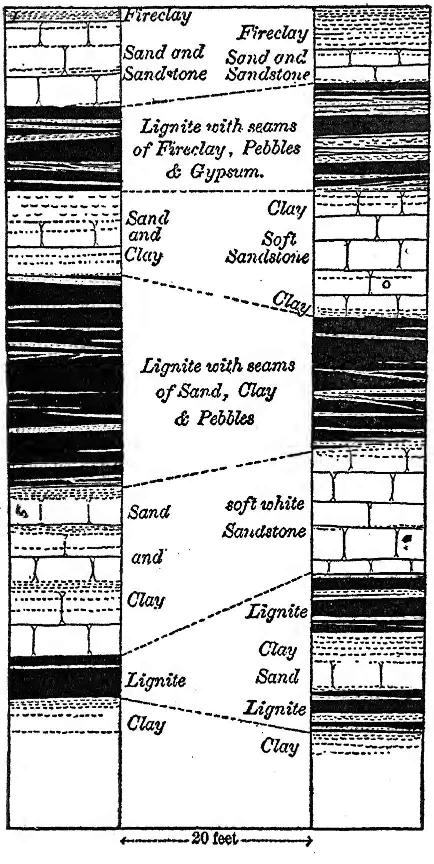


FIG. 405. — Parallel vertical or columnar sections on the face of Pulpit Rock, near Colorado Springs, through identical strata, and only 20 feet apart; illustrating rapid lateral changes in the character of the strata. (From Crosby.)

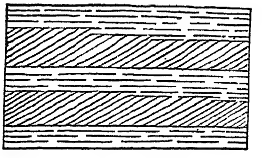


FIG. 406.—Diagram showing the type of cross-bedding which is characteristic of torrential river deposits. (Compare with Eolian cross-bedding, Figs. 372 *b*, and 374–377.)

Cut-and-fill Structure. — This is especially characteristic of the coarser river deposits, such as those formed in alluvial fans and waste-filled basins. It may, however, also occur in the finer sediments. It is characterized by abrupt channels which cut off, or are excavated into, the older layers, and are filled by a part of the next higher layer. They indicate the channelling so characteristic of the surface of alluvial fans, and the subsequent filling in of these channels where a change in direction of the current has occurred and new deposits are added.

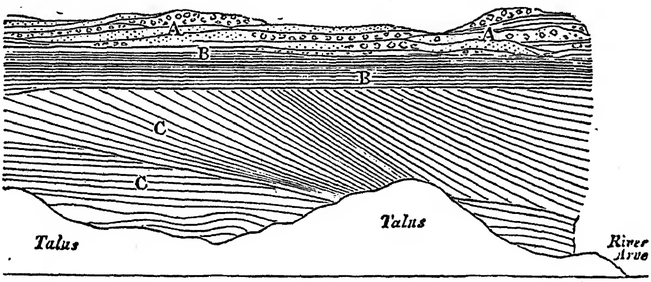


FIG. 407. — Section of a sandbank in the bed of the Arve at its confluence with the Rhone, showing the stratification of deposits where currents meet. (From Lyell's *Principles.*)

Ripple Marks. — These structures are formed under varying conditions. In river deposits, they generally represent a series of low, parallel ridges, one side of which is steeper than the other (Fig. 408 *a*). These are the current ripples which form at right angles to a gently flowing current in the shallow pools, as sand dunes form at right angles to the direction of the wind. Such ripples are, however, by no means confined to river deposits, but may occur in all strata laid by and in shallow water, and occur in wind deposits as well. (See Fig. 371, p. 453, and Fig. 453, p. 537.)

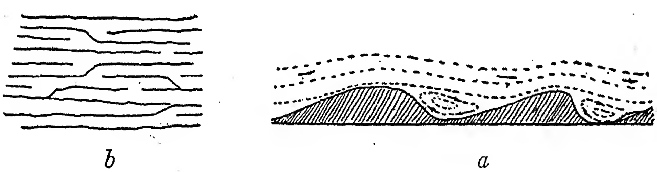


FIG. 408. — Diagram showing: *a*, the formation of current ripples (after Darwin); and *b*, plan showing arrangement of ripples in parallel lines with transverse connections. (After Walther.)

Rill-Marks. — These are formed upon the mud surfaces of flood-plains and playa surfaces, where a small stream of water trickles from a bank or bubbles up from beneath and runs away, spreading into numerous distributaries, which become finer and finer outwards until they fade away. Such spreading rill-marks are the reverse of those most common on the shore in which the channels

converge like the branches of a stream system. When covered by sand, these rill-marks may be preserved in relief, and they often have a strong resemblance to some form of plant, for which fossil rill marks have often been mistaken (Fig. 409).

FIG. 409. — Fragment of a relief mold of rill-marks on the under side of the stratum which covered the layer in which the rill-channels were originally made. Triassic sandstone, Portland, Conn. (After Newberry.)

Mud-cracks. — These are most characteristic of the playa and flood-plain surfaces and are formed by contraction of the surface layer of mud in drying. As a result, such layers split up into polygonal blocks, which generally curve gently upward at the margin, producing a saucer-shaped surface. (See Figs. 392, p. 476, and 395–396, pp. 479, 480.) The cracks increase in width and depth with progressive drying, and this may go on to such an extent that their depth is measured by several feet. Ordinarily, however, the depth is not over one, or, at most, a few inches. A covering of sand preserves these mud-cracks, as it fills the fissures between the blocks (Fig. 410). On the under side of the sand layers when hardened, the polygonal surfaces will be gently convex and bounded by raised ridges of hardened sand. Mud-cracks may be formed on tidal flats which are exposed for a long period of time. Ordinarily, however, such flats do not dry sufficiently between tides to permit the formation of mud-cracks, or if they are formed, the mud does not harden sufficiently to withstand the softening effect of the returning tide. Figure 411 shows a photograph of an ancient clay-rock with very narrow mud-cracks.

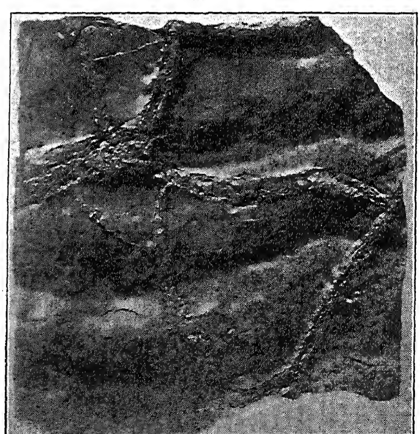


FIG. 410. — Fossil ripple marks cut by mud-cracks which have been filled in by other material. (Reverse.) (U. S. G. S.)

Raindrop Impressions. — These are also most typical on the mud surfaces of flood-plains and playas (Fig. 412). When raindrops strike the mud sharply, they leave a concave impression, around the margin of which the pressed-out mud

forms a low rim. If the raindrop strikes obliquely, as when driven by wind, the impression will be asymmetrical, being deeper on the side from which the rain struck and the wind blew, while an asymmetrical bordering rim is also produced. Raindrops also may be preserved in relief on the under side of a stratum subsequently deposited upon the pitted surface.

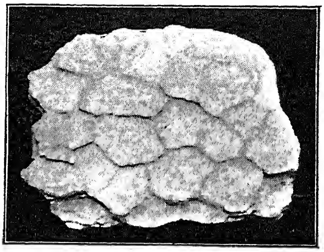


FIG. 411. — Photograph of a specimen of clay rock from the Silurian formation of Pennsylvania (Longwood shale), showing mud-cracks formed upon an ancient river flood-plain or playa. The fissures in this case are very narrow, although the structure affects the rock mass for a depth of many inches. About one eighth natural size. (Columbia University collection; photo by B. Hubbard.)

Footprints. — The footprints of land animals are most commonly preserved in the flood-plain and playa deposits when these are subject to hardening by exposure. Footprints of the camels of a caravan in the Sahara were still distinctly recognizable fifteen years later in the hardened mud. Such footprints may also be preserved in relief on the under side of a covering stratum. (See Fig. 398, p. 482.)

Clay Galls. — When only a thin layer of mud is deposited on the flood-plain or playa, this may curl up into fine spirals resembling wood shavings, and these may be transported by the wind and come to rest in sands either of eolian or river-laid origin. On being wetted, these clay shavings suffer compression and eventually form only a thin oval plate or film of clay on the sand mass. Such "clay galls" are a characteristic feature of many hardened sand deposits of subaërial origin.

Red Color of Ancient River-laid Deposits. — Many ancient deposits which by their general character suggest their origin as river deposits now have a red color, such as is seldom if ever seen in modern river sediments, where the prevailing tones are dark or light grays or blues or else yellows. The latter is most commonly met with in alluvial fans and plains formed in regions of little vegetation, because of protracted dryness of climate for at least part of the year. This yellow color, as already described in an earlier section (page 459), is due to the oxidation and hydration of the disseminated iron in the sediment, and is especially noticeable where such sediments are fine grained with much clay or rock flour. Where much vegetation is present, such oxidation is not readily effected, nor can subsequent oxidations of the sediments take place easily when the deposit is saturated with ground water, which prevents the free access of the oxygen except in so far as the water carries it. In dry

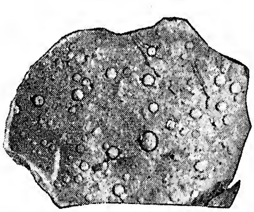


FIG. 412. — Raindrop impressions in a layer of hardened clay from a modern roadside surface. About one half natural size. (B. Hubbard, photo.)

climates, however, where the level of the ground-water sinks low, the upper layers of the deposit are sufficiently dry to permit the entrance of the air, and here oxidation is accomplished. If this can take place for each successive layer added to the surface of the alluvial fan or plain, the entire deposit will come to have its iron content oxidized throughout. In the course of time, this hydrous iron oxide will lose its water, and the color will change from yellow to red. In this manner may be explained many of the extensive red-bed formations found in several geological series, though at the time of deposition such beds were yellow rather than red.

Glacial Transportation and Deposition

Transportation

Modern glaciers transport clastic material partly upon their surfaces (superglacial), and partly within their mass (englacial), and partly frozen into their bottoms (subglacial). All the material transported by ice, whether modern or ancient, is called *glacial drift*, while the large transported boulders are termed *erratics*. The subglacial material is derived in part from the erosion of the rock floor by the glaciers and in part from material which is loosened and pried off on the margins of the cirque, and especially in the bergschrund (p. 366). Englacial drift originates partly from the material carried up from the bottom wherever an oblique shearing plane permits faulting in the ice, the mass from behind overriding that in front of it and carrying its débris upward. Part of the englacial material is, however, of superglacial origin and represents the fragments which have fallen into the crevasses or otherwise become inclosed in the ice mass. Superglacial material is derived in various ways. In the valley glaciers, the rock fragments falling upon the ice from the valley sides, or sliding down in avalanches, accumulate upon the side of the ice, and as the glacier moves along, such accumulations are strung out in lines of drift along the margin. This constitutes the *lateral moraine*. (See *ante*, p. 368.) Where two glacial streams unite, their adjoining lateral moraines become confluent and are continued as a *medial moraine* (p. 370).

These moraines are, however, also fed from below; for it is known that in a moving glacier there are diverging currents, by virtue of which the lower ice layers move outward and upward along the sides of the glacier as well as toward its front (Fig. 413 *a*). Such currents carry material from the bottom upward, and as this rises and the inclosing ice melts, the material becomes incorporated in the lateral moraines. Furthermore, when two ice streams meet they never

commingle as two water streams will, but flow along side by side with more or less independence. The upward currents which formed part of the lateral moraine above the point of junction will continue and the material brought up along the sides of the glaciers in contact with one another will thereafter contribute to the medial moraine (Fig. 413 *b*).

FIG. 413 *a*. — Diagram showing ice currents carrying sub-glacial material upwards to form lateral moraines. (After Chamberlin and Salisbury, *Geology;* by permission of Henry Holt & Co.)

This change from subglacial to englacial and finally to a superglacial position of the material makes possible the renewal of moraines on the surface of the ice, when great floods of water from prolonged melting have washed the surface clear of débris. Such renewal of moraines after the removal of the older ones by a flood has actually been observed in glaciers of the Alps.

Large ice masses like the ice-caps of Iceland and Scandinavia and the continental ice-sheet of Greenland have little or no superglacial material, since they are not confined in valleys. It is true that near the margin of the Greenland ice-cap, rocky peaks or nunataks project through the ice, and these furnish a

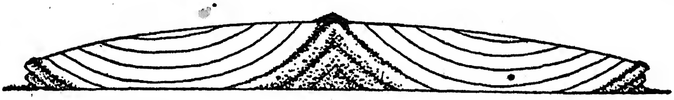


FIG. 413 *b*. — Diagram to illustrate ice currents carrying sub-glacial material upwards to form a medial moraine. (From Chamberlin and Salisbury, *Geology;* by permission of Henry Holt & Co.)

certain amount of débris which accumulates on its surface. Where upward currents are developed in the ice which is forced to pass between two adjoining nunatáks, a semicircular morainic band may be produced, extending from one nunatak to the other. (See page 386.) But on the whole, ice-sheets transport their débris primarily as subglacial material, and as englacial, where local upward currents or shearing planes cause the subglacial material to rise. Such material is commonly characterized by the polishing and scratching of all the coarser fragments, a feature not characteristic of superglacial accumulations of rock falls. (See Fig. 360 *b*, p. 435.)

Deposits Formed by Modern Glaciers.

Terminal Moraine. — Modern valley or mountain glaciers deposit their load of débris chiefly at their lower ends, where melting takes place (Figs. 414, 415). This constitutes the *terminal moraine*, which is composed of superglacial, englacial, and subglacial material more or less intimately commingled and showing no regularity

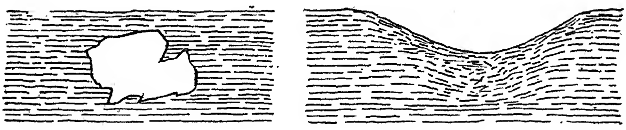
of structure. Many ice blocks are buried in such a terminal moraine, which, on subsequent melting, will cause a caving-in of

FIG. 414. — Terminal moraine topography at foot of Kotsina Glacier, Alaska. (Photo by Schraeder, U. S. G. S. Courtesy D. W. Johnson.)

FIG. 415. — Terminal moraine of a former glacier, Oregon.

this covering of débris, and the production of a cup or kettle-shaped hollow, a feature to which the name *kettle-hole* is applied (Fig. 416).

These may be dry or contain water forming a glacial pond (Fig. 417). Such terminal moraines are best developed where the ice front rests for a considerable period of time at the same point, which implies that the rate of melting at the front and the rate of



A *B*

FIG. 416. — Diagrams to illustrate the mode of formation of kettle-holes in glacial deposits. *A*, a portion of a glacial sand-plain burying a boulder of ice; *B*, the same after the ice-boulder has melted, and the sand caved in to form the nearly circular kettle-hole.

ice advance are equal and balance each other. When there is no such equality, the material left on melting will be scattered over a belt of greater or less width and form no pronounced terminal moraine. If the stream issuing from the front of the glacier is very strong, a large part of the glacially transported material may

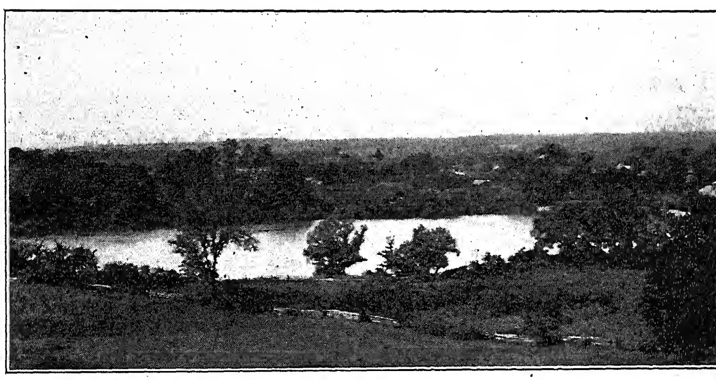


FIG. 417. — A kettle pond in a glacial landscape.

be carried away by it, and the terminal moraine will suffer accordingly. When well formed, such a moraine may reach a height of more than two hundred feet, but heights of 100 to 200 feet are more frequent.

Submarginal Moraines. — In some valley glaciers the material carried toward the sides of the glacier by the diverging ice currents

may accumulate there as a submarginal moraine, and become exposed on the melting away of the glacier. Such moraines accumulate when the supply of bottom débris is large as compared with the carrying power of the glacier. Submarginal moraines are distinguishable from lateral moraines, which may be let down upon the valley sides on the melting of the ice, by the fact that the submarginal accumulations are very compact from the pressure of the ice and that the stones and boulders in them are scratched and polished, features not found in the lateral superglacial moraines.

Ground Moraines. — When the supply of drift in the bottom of the ice is larger than can be moved along by the glacier, part of it will remain upon the bottom as ground moraine and will be overridden by the ice as it moves onward. Such material will be thoroughly compacted and will consist of an intimate and irregular mixture of rock-flour, sand, and striated pebbles and boulders, a mixture to which the name *till* is applied. In modern glaciers, this accumulation takes place chiefly near the front, where the ice is thinner, or behind an obstruction over which the ice moves but behind which it leaves part of its débris.

Deposits Formed by Former Ice Sheets

From the wide extent of surface deposits which have all the characteristics of glacially transported material, as well as from scratched and polished rock surfaces (Fig. 359, p. 434) and the effects of erosion upon the landscape such as are known to be produced by moving ice, it has become apparent that a considerable portion of northern North America and western Europe was covered by continental ice-sheets during a period preceding that in which we live, and from the association of these deposits with the remains of early man in Europe, we recognize that this ice-covering still existed after man had made his appearance upon the earth, though he had not yet spread widely over its surface. The deposits formed by these ice-sheets consist mainly of ground moraines and terminal moraines and the various modifications of these, together with the deposits formed by the streams from the melting ice, both upon the land and in standing bodies of water, either permanent or temporary.

Ground Moraines; Drumlins. — Vast areas of northern North America and western Europe are covered by the ground moraine

of the ice of the last glacial period. This is a till or boulder clay which consists of a heterogeneous mixture of fine and coarse material, with polished and striated boulders and without strati-

FIG. 418. — Typical section of glacial till exposed by cutting a road through the southern end of a drumlin, Whitewater Quadrangle, Wis. Note the unstratified and unassorted character of the material. The appearance of the pebbles in this till is shown in Fig. 419. (Photo by Alden; from U. S. G. S.)

fication or assortment. It is often so thoroughly compacted that it requires almost as much labor for its removal as does a mass of solid rock, on which account it is commonly known as *hardpan* (Figs. 418, 419). This deposit of till often fills in irregularities in

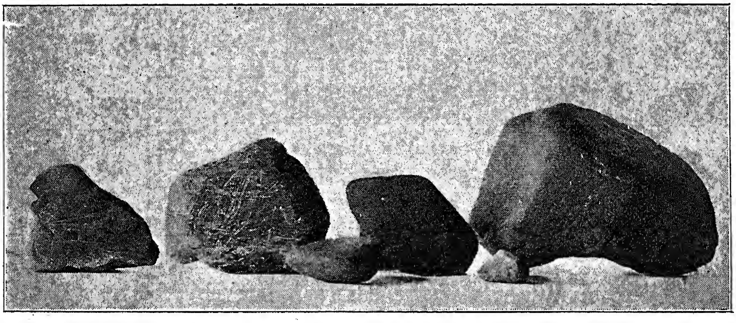


FIG. 419. — Glaciated pebbles and boulders from drift of North America, showing characteristic form and scratches. (Photo by Alden; from U. S. G. S.)

the rock topography beneath it, and so produces a more or less monotonous surface. At other times it rises in regular rounded or elliptical hills of elongate form, with their major axis in the

FIG. 420 *a*. — Drumlin near Groton, Mass. (After Frye.)

direction of the ice movement. Such hills are known as *drumlins*, and they form a characteristic feature of the topography of eastern Massachusetts, parts of New York, Wisconsin, and other areas in the glaciated regions (Figs. 420 *a*, *b*).

The thickness of the till varies greatly, rising to several hundred feet in some drumlins, and falling to a few inches elsewhere. The rock surface below the till is generally smooth, showing much erosion and polishing by the ice, and generally exhibiting a series of parallel scratches which indicate the direction of the ice movement (Fig. 359). In some cases, however, deep grooves and flutings were formed, where large boulders were moved along upon soft rocks into which they gouged deeply. Such glacial groovings have been found wonderfully developed on the limestone surfaces of Kelley's Island in Lake Erie, and in many other regions (Fig. 421).

FIG. 420 *b*. — Section of part of a drumlin, near Boston, Mass., showing the heterogeneous mixture of fine and coarse material including boulders. (Photo by the author.) (See also Figs. 447, p. 531, and 726.)

When the ice first accumulated, many parts of the country were covered by a mantle of residual soil due to the weathering of the rock. This material, which included much clay, was the first to be carried away, and

where it was deposited the resulting till consists partly of clay. Subsequent erosion by the moving ice, however, produced only the finest rock-flour, or mechanically ground-up undecomposed

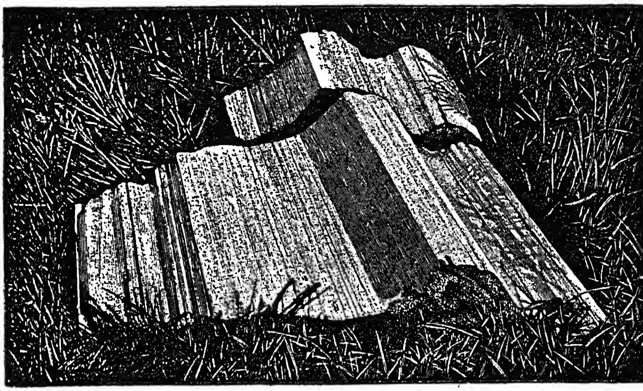


FIG. 421. — Glacial fluting on limestone, Kelley's Island, Lake Erie.

rock, besides the larger fragments, and in consequence such material predominates over the clay, which may be largely or wholly wanting.

Terminal Moraines. — Whenever the ice halted for a period of time along a given line, a terminal moraine was built up from the subglacial and englacial material, the size of the moraine de-

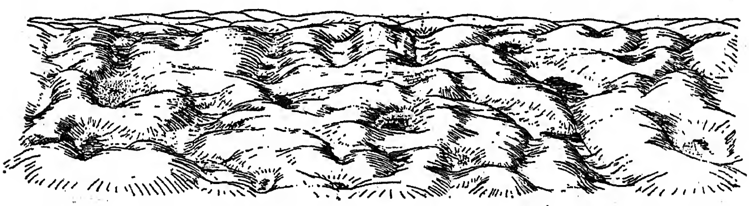


FIG. 422. — Bird's eye view of about 2 square miles of terminal moraine. Lakes shown by horizontal shading; swamps are dotted. (Drawn by Fred K. Morris.)

pending upon the length of time during which the ice front was stationary. Such moraines exhibit the characteristic kettle topography (Fig. 422) due to the inclosure of ice blocks which subsequently melted, while in many cases the removal of the finer surface material by the waters from the melting ice has left them covered over with great boulders. Whenever the sea or

other agent has cut into such a moraine, its structure is seen to consist of irregular accumulations of sand and finer material with many boulders, often of large size and of heterogeneous char-

FIG. 423. — Crest of northern frontal moraine, looking northwest. Dogtown Common. (After Shaler, U. S. G. S.)

acter. The so-called "backbones" of Long Island and Cape Cod are formed by the terminal moraines, and the Narrows in New York harbor represent a cleft in the great terminal moraine, the cut ends of which can be seen on both sides, modified of course by man's activity. This moraine and many smaller ones to the north of it can be traced with more or less continuity for long distances across the continent, being recognizable by their topography and internal constitution.

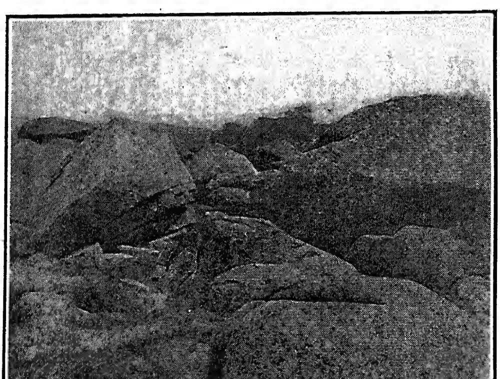


FIG. 424. — Boulder moraine, Dogtown Common, Cape Ann. These boulders are chiefly granite, and they are piled up in great heaps with little or no fine material between. (Photo by the author.)

Boulder Trains and Moraines. — In some cases the moraines appear to consist almost wholly of large and small boulders, forming

a topography of striking wildness and complexity. Such a moraine covers a part of the surface of Cape Ann in eastern Massachusetts,

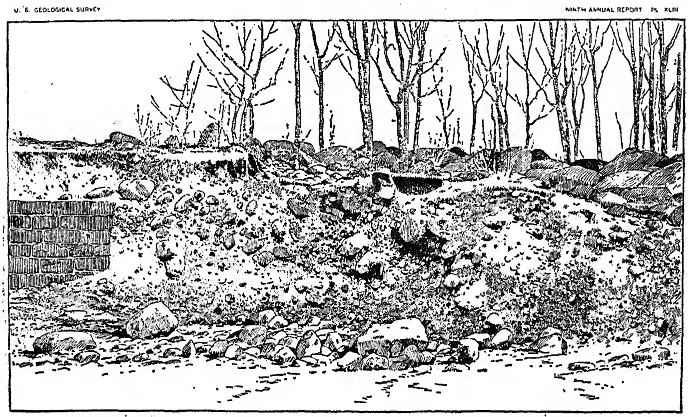


FIG. 425. — Section of frontal moraine on side of Warner Street, Gloucester, Mass. (After Shaler, U. S. G. S.)

its most picturesque portion near Gloucester being known as "Dogtown Common" (Figs. 423 to 425). This moraine is believed to be the result of a disturbance, by readvance of the ice, which by shaking up an older moraine caused the finer material to settle down between the coarse blocks, which then alone appeared upon the surface. Part of the fine material may also have been washed away by glacial waters. Sometimes trains or long lines of boulders alone mark the moraine, or they may form a line in front of some projecting rock mass from which they were derived. Some of these glacial boulders are of astonishing size (Fig. 426).

FIG. 426. — House Rock, a large glacial boulder or erratic near Hingham, Mass. Its size is indicated by a comparison with men standing near it. (Photo by the author.)

Interlobate Moraines. — As the ice which covered much of the northern lands consisted of several distinct lobes which abutted

one against the other, moraines were formed between the abutting lobes by the drift brought to the margin from each lobe. Such moraines therefore often extend more or less at right angles to the main terminal moraine, and their opposite sides may be composed of very different materials. The great north-south moraine which forms the hills of Plymouth and extends southward to Woods Hole in Massachusetts is such an interlobate moraine.

Modified Deposits of the Great Ice Age

The waters resulting from the melting of the ice-sheet, on issuing at its front, formed many special types of deposits, recognizable by their form and structure. These, as a rule, are more or less stratified, often pronouncedly so, and on this account, the modified drift is also spoken of as *stratified drift* in contradistinction to the *unstratified drift* or till. The most important of such deposits are the kames, apron-plains, sand-plains or glacial deltas, and the eskers.

Kames. — These are more or less conical mounds of sand deposited at the ice-front by temporary glacial streams. They are not uncommon in the moraine belt, of which they may constitute a part.

The Apron-plain. — This is formed of the outwash along the ice front, and generally lies in front of the terminal moraine.

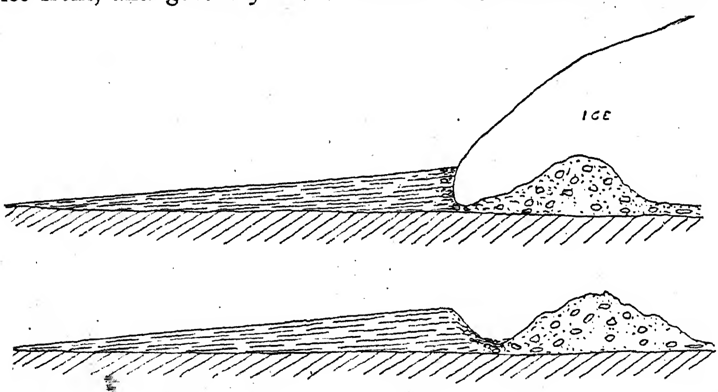


FIG. 427. — Diagrams illustrating the mode of formation of the frontal apron-plain and its relation to the terminal moraine. (Adapted from J. B. Woodworth.) The ice-front partly covers the terminal moraine which is submarginal. In front of the ice the stratified sands washed outward by the glacial waters build a gently sloping apron-plain. When the ice melts away, a depression or "fosse" appears between the moraine and the apron-plain, the upper end of which, formerly banked against the ice, now slumps, and forms a steep back- or ice-contact slope.

Near the moraine border there is generally a depression or *fosse* which may be occupied by a chain of lakes, and from it the apron- or outwash plain rises, often with steep slopes, where the sand rested against the face of an ice mass which occupied the place now marked by the fosse (Fig. 427). From the summit of this slope the plain descends with a very gentle inclination and generally a nearly smooth surface which may dip into the sea, as in the case of the outwash plain which forms the southern half or more of

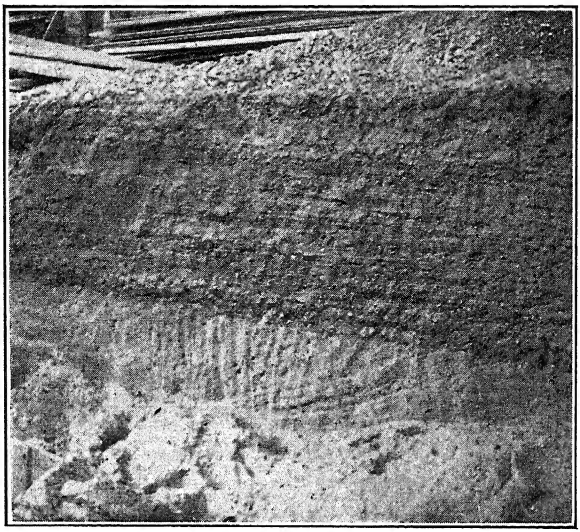


FIG. 428 *a*. — Section of a glacial delta or sand-plain showing fine-grained fore-set beds dipping to the left, covered by coarser top-sets. College Hall Hill, Wellesley, Mass. (Photo by W. P. Haynes; courtesy of Prof. E. Fisher.)

Long Island and that which forms the main southern part of Cape Cod. Commonly a series of transverse channels, the paths of the main streams from the ice, transects the outwash plain, and these channels may be dry or filled with water (as on the Nantucket plain). Kettle-holes may also occur on this plain, and in regions of high ground-water level, as near the coast, these may be converted into ponds. Boulders are rare on such a plain, the material being mostly sand, generally well stratified.

The Sand-plain or Glacial Delta. — Where a body of water was held up by the ice front in a valley which sloped toward it, a stationary lake was produced, the level of which depended on the

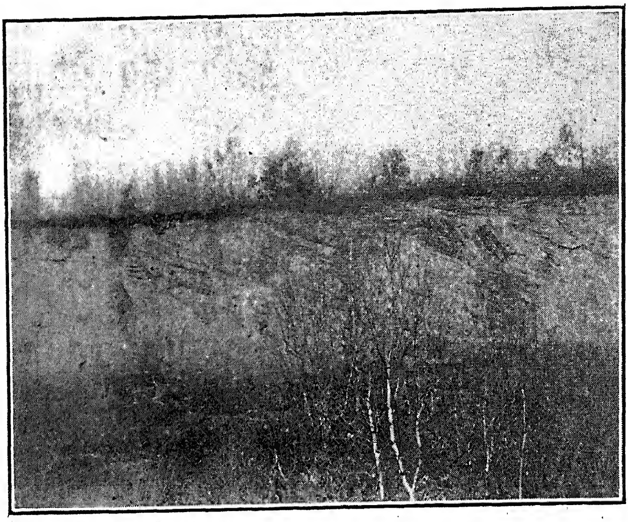


Fig. 428 *b*. — Section of a glacial delta or sand-plain, showing the level top, the steeply dipping fore-set beds, and the horizontal top-set beds. Brockton, Mass. (Photo by the author.)

Fig. 429. — Ice contact slope of a glacial sand-plain or delta. Note the steep character of the slope. (Photo by the author.)

elevation of the lowest exposed point in the rim of the valley, as does the level of the Märjelen Lake by the side of the Aletsch glacier in Switzerland, on the level of the divide which separates its valley from another on the east. (See p. 362.) Into such a body of water deltas may be built by the sands washed down from the ice, and such deltas will have all the characters of normal stream

FIG. 430 *a.* — Diagram illustrating a successive series of sand-plains or glacial deltas built into a temporary lake held up by an ice-dam in a northward sloping valley. The southern plains were built when the lake stood at its highest level, this being indicated by the edge between the surface and frontal slope. As the ice front melted backward lower outlets were uncovered and the level of the lake sank. Then the lower deltas on the north were built.

deltas built into permanent lakes, including lobate front and a series of sloping fore-set and nearly horizontal top-set beds (Figs. 428 *a*, *b*). As ice boulders may be buried in such a delta, kettle-holes may develop subsequently by their melting, and these are not uncommon in the larger deltas of this type. The most characteristic feature of these deltas, however, is due to the fact that on the

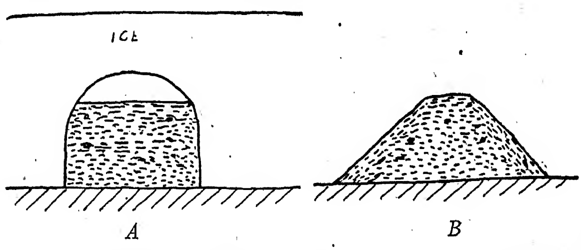


FIG. 430 *b.* — Diagrams showing the origin of eskers. *A*, A tunnel under the ice, nearly filled with sand and gravel by the subglacial stream which built up its bed to the level of the outlet, or the level of the lake held in front of the ice. *B*, The same deposit after the melting of the supporting ice-walls. Slumping has produced the characteristic steep side-slopes.

melting of the retaining ice wall of the lake, this will be drained, and the delta will then form a plateau-like elevation in the midst of the valley. The side of the delta which rested against the ice will, by slumping, become a steep slope — often as steep as 30 degrees — and one easily distinguished by its angle and general outline from the frontal slopes of such deltas (Fig. 429).

When successively lower passes are opened in the valley side by the melting back of the retaining ice front, the level of the lake

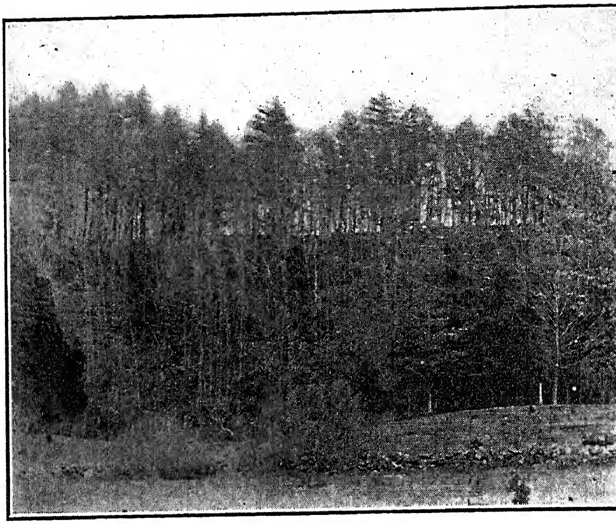


Fig. 431 *a*. — An esker, near East Weymouth, Mass. Seen from the side. (Photo by the author.)

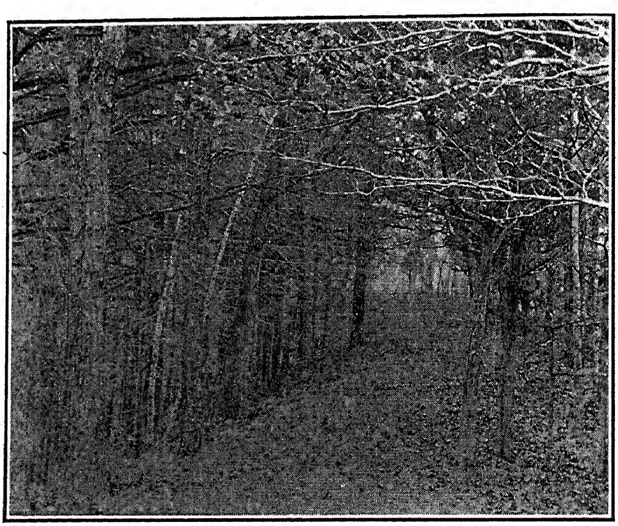


Fig. 431 *b*. — Top of the esker shown in Fig. 431 *a*, East Weymouth. (Photo by the author.)

will sink in accordance therewith, and a succession of plains or deltas at lower levels may be built up (Fig. 430 *a*). There are many such plains in the valleys of Massachusetts which show the progressive lowering of the old ice-dammed lakes, the shores of a number of which have been traced and the successive outlets located, in conformity with the levels indicated by the heights of the abandoned deltas.

Eskers. — Streams flowing in ice gorges near the front of the great ice sheet or in tunnels beneath it, built up their beds by depositing sand and gravel on their floors, until a height was reached which corresponded to that of the standing water level in front of the ice or the elevation of the rocky *col* across which the stream had to discharge. During their formation these deposits rested against the side of the ice gorge or tunnel, but on the melting of the ice this support was removed, and the sides of the sand and gravel mass began to slump and come to rest at the steepest angle consistent with the nature of the material (Fig. 430 *b*). In this manner, more or less winding ridges of triangular section were formed, often extending across country for many miles like a huge railroad embankment, but of somewhat variable height and generally winding course, this course being that of the stream which made the deposit (Figs. 431 *a–c*). Such ridges are known as *eskers* or *osars*, and they abound in New England, in Scandinavia, and in other regions formerly covered by the ice and of a topography favorable to their formation. They often constitute striking features of the landscape. Not all eskers were formed in this manner, some probably representing accumulations of sand and gravel in gorges cut into the ice, or in crevasses open to the sky.

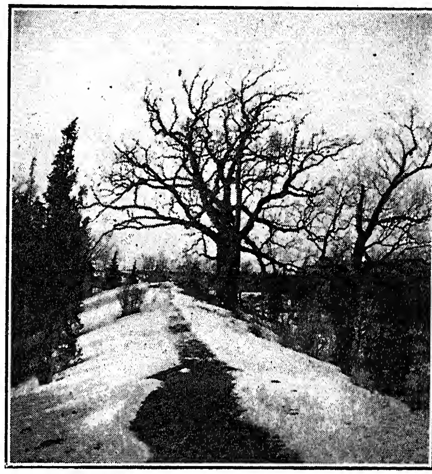


FIG. 431 *c*. — A small esker, winter scene among the Waverly Oaks, Waverly, Mass. (Photo by the author.)

Ancient Glacial Deposits

In very ancient geological formations in India, South Africa, Australia, and South America great beds of rock are known, which have all the characteristics of a glacial till, including the polished and striated boulders and bed-rock (Fig. 360 *a*, p. 435). These rocks, known as *tillites* or consolidated tills, are interpreted as the deposits of ice-sheets which covered these regions in former geological periods. Similar, even more ancient, glacial deposits have been reported from Canada and elsewhere, and others from northern Norway. They will be considered more fully in the section on historical geology under their respective periods.

CHAPTER XVII

TRANSPORTATION, SORTING, AND DEPOSITION OF CLASTIC MATERIAL IN THE SEA

The Geographical Subdivisions of the Sea

When we speak of the sea we refer to the entire extent of the connected salt waters of the earth, those that lie between the continents and those that lie within them. The completely enclosed salt water lakes such as Great Salt Lake, the Caspian Sea (lake), and the Dead Sea (lake) are not included here, though it is a general European custom to speak of such water bodies as seas (German, *Seen*). The term *seas* is most commonly applied to the more or less, but never completely, enclosed portions of the sea, such as the Mediterranean Sea, the Black Sea, the Yellow Sea. Completely enclosed bodies of water are properly called lakes, whether they are fresh or salt, though it will probably be difficult to correct such popular misnomers as "The Dead Sea," "The Caspian Sea," etc., many of which received this appellation when it was believed that they were a part of the great salt sea.

Other loosely used geographic terms are *gulf* and *bay*, which are indiscriminately applied, sometimes to open and sometimes to partly enclosed marginal bodies of water; sometimes to deep bodies of this type, sometimes to shallow. It is therefore important that certain more precise terms should be used, terms which designate the various types of water bodies, divided not only according to form and location, but also according to depth and relation to other water bodies.

The Oceans or Intercontinental Seas

The Three Continental Masses. — From our present point of view, we may consider that there are only three continental masses, to one or the other of which all the so-called continents of the geographer belong. These continental masses are the three great

land blocks of the earth's crust, and although several of them seem to be nearly or quite separated into distinct *continents*, they are in reality units, and in former periods of time they were in some cases more intimately united than they are to-day. Named in the order of their magnitude, these three continental masses are: 1. *The Old World Mass*, comprising the geographical continents of Europe, Asia, Africa, and Australia; 2. *The New World Mass*, comprising the geographical continents of North and South America; and 3. *The Antarctic Mass*, forming a single Antarctic continent.

The Four Oceans. — Between these continental masses lie the oceans, which are thus truly intercontinental in position, and represent the oceanic blocks of the earth's crust which probably, because of their greater density, have a sunken position with reference to the continental blocks. In the opinion of many students of the earth, these differences of relative position have been constant since the earliest recorded geological time, though there are others who hold that at one period or another some of the oceanic blocks were also elevated to such an extent that their surfaces appeared as land above the sea-level. Named in the order of their magnitude, the four oceans of the earth are: — 1. The *Pacific Ocean*, lying between the Old World block on the west and the New World block on the east, the convergence of which bounds this ocean on the north, while the southern boundary is formed by the Antarctic continent; 2. The *Atlantic Ocean*, lying between the same continental masses except that the Old World block is on the east and the New World block on the west, while the Antarctic block also bounds it on the south, and the convergence of the other two blocks on the north; 3. The *Indian Ocean*, lying between the Old World block on the north, and the Antarctic block on the south, while on the east and the west it becomes more or less confluent with the Pacific and Atlantic oceans, respectively; 4. The *Arctic Ocean*, the smallest of all, which lies between the northern ends of the Old and New World blocks, and is more or less completely bounded by them (Fig. 432).

The Continental Shelf. — At present the oceans are overfull of water, and so they spread out over the margins of the continental blocks, in some places for a distance of only a few miles, in others for a hundred miles or more. This margin has in general the form of a shelf or gently seaward sloping platform, partly due to erosion of the land margin and partly to deposition. From this shelf arise the

continental islands which are either residual masses left by the erosion of the edge of the land, or have been built up on the shelf, by clastic sediments from the land, by organisms (coral reefs, etc.),

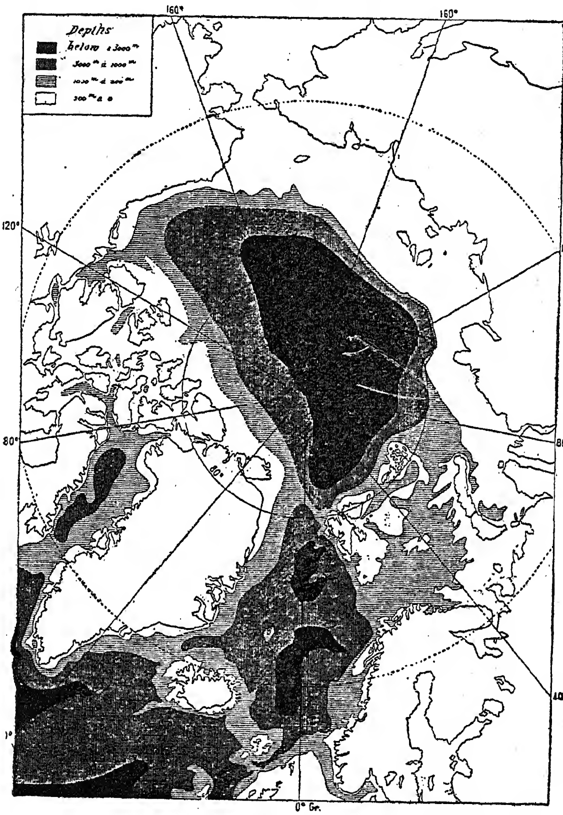


FIG. 432. — Map of the Arctic Ocean and a part of the North Atlantic Ocean, showing the depths. The continental shelf (0–200 meters) is left in white like the continents. Note its great width off the Eur-Asian coast (long. 40° E. to 160° W.). Also note the many epicontinental seas or shallow indentations of the land. The Baltic Sea (between long. 0° and 40° E. is an *epeiric* sea. The bathyal zone is shown by the lighter shading (horizontal lines, 200 to 1000 meters) and the deeper bathyal zone by the darker shading (cross-lines 1000–3000 meters). These two form the continental slope. The abyssal district is represented in solid black. Note the double character of the Arctic Ocean and the submerged ridges which divide it from the North Atlantic. These are the Wyville-Thompson ridge between Scotland and the Faroe Islands, the Faroe-Iceland ridge between these islands, and the Denmark straits ridge between Iceland and Greenland. (After Nansen; from Grabau's *Principles of Stratigraphy*.)

or by volcanic eruptions. The depth of water over this shelf ranges from zero to about 100 fathoms (600 feet), at which point, approximately, the main margin of the continental mass is located. This margin is also called the *edge of the continental shelf* (Fig.

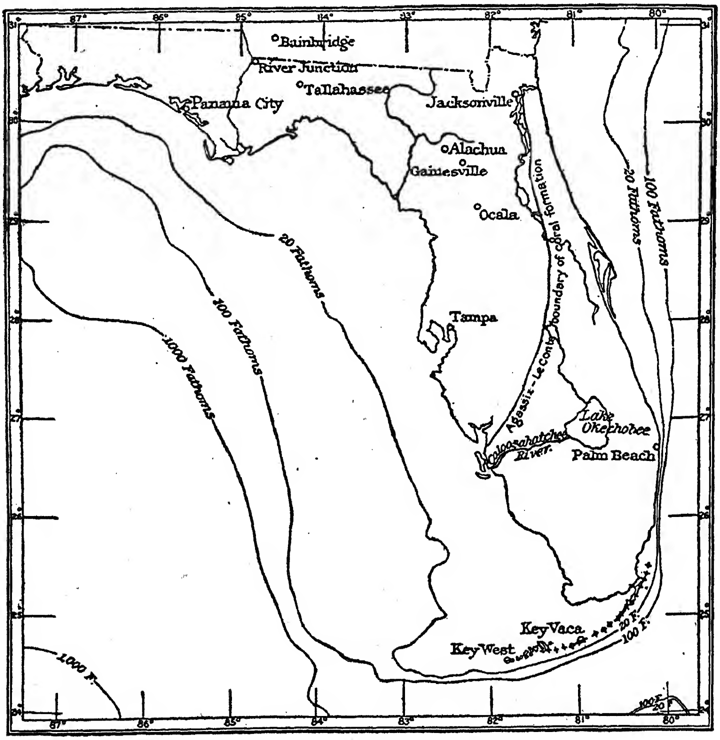


FIG. 433. — Map of the peninsula of Florida, showing the bottom contours of the surrounding sea. The line of keys and old reefs is indicated by crosses. (After Vaughan.) The 100-fathom contour line marks the edge of the continental shelf. Note the width of this shelf on the west, and its narrowness on the southeast where it is swept by the Gulf Stream. Note that on the west the descent from 100 to 1000 fathoms takes place in a shorter distance than the descent from 20 to 100 fathoms. The Keys are continental islands of organic origin built upon the shelf. The part of the sea-bottom bounded by the 1000-fathom line represents the abyssal district. (Compare Fig. 438, p. 519.)

433). It is upon this shelf that the epicontinental seas are located, while deeper seas transect it. (See Fig. 434.) The continental shelf is also the chief region of clastic deposition in the open sea, though of no greater importance than some of the seas next to be described. (See Fig. 438, page 519.)

The Epicontinental and Intracontinental Seas

Upon the edge of the land, that is, upon the continental shelf, there are a number of distinct water bodies more or less outlined by land extensions, submerged ridges, or islands rising from these. These are called *epicontinental seas* (*epi*, upon) because they lie upon the continent. Some of these extend far into the land masses (*epeiric seas*), but are still shallow films of sea-water resting upon the land. Examples of these are seen in the Baltic Sea, and in Hudson Bay. Again, the edge of the continental shelf may be deeply intrenched, excavated, or hollowed by down-sinkings, and such excavations may also extend far into the land. These are the true *intracontinental seas*, because they lie within the continental mass. They are illustrated by the Gulf of California (Fig. 434), and by the Red Sea (Fig. 437). The principal types may be briefly noted.

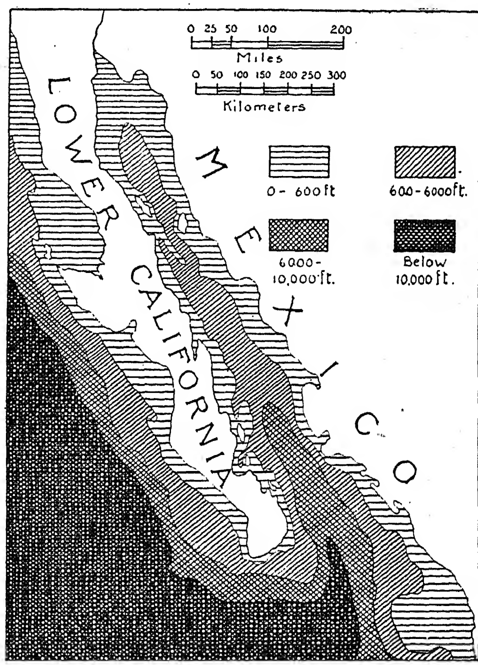


FIG. 434. — Map of the Gulf of California, a typical *funnel-sea* of the narrow type, transecting the continental shelf, which is represented by the horizontal lining (0–600 ft.). Note the regular and progressive deepening of this funnel-sea and compare with the Red Sea, a typical mediterranean sea (Fig. 437). On the western border of Lower California is a partly enclosed epicontinental sea, the Bay of San Sebastian Vizcaino. The continental slope is shown by diagonal lines (600 to 6000 ft. or 100 to 1000 fathoms), though the next zone might also be included here (6000 to 10,000 ft.). Below that is the deep sea (10,000 feet and lower). (See section, Fig. 438.)

Intracontinental Seas

Funnel Seas. — Where the continental margin is deeply excavated or incised, so as to form a trough which extends into the land with regularly narrowing sides and a regularly rising bottom, a *funnel sea* is produced, so called because its form may be compared with that of one half of a longitudinally divided funnel. The Gulf of California is a typical example, for not only do its sides converge toward the head, but its floor rises progressively (Fig. 434). If the sea-level should sink or the land block rise, this funnel would be gradually emptied by the withdrawal of the water and no residual

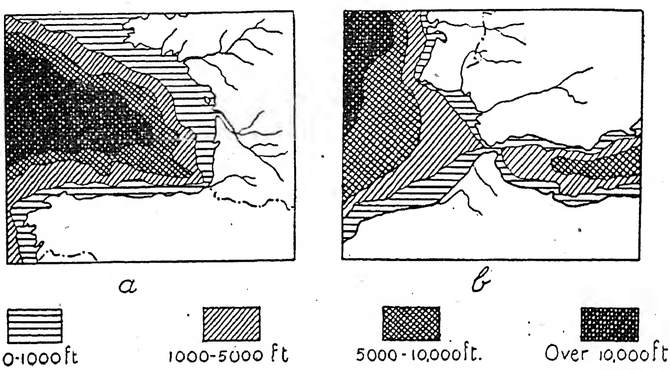


FIG. 435. — Broad or Biscayan type of funnel-seas. *a*, Bay of Biscay between France and Spain, a closed-head funnel-sea; *b*, Gulf of Cadiz, an open-head funnel-sea of this type, receiving the waters from the Mediterranean through the Straits of Gibraltar.

lake would remain. The California funnel sea represents the narrow type; a broader type is represented by the Bay of Biscay on the west coast of Europe, which differs from the California type only in the more rapid convergence of its sides and corresponding rise of its bottom (Fig. 435 *a*). A modification of this type is seen in the Gulf of Cadiz, which receives the outlet of the Mediterranean Sea (Fig. 435 *b*). This may be referred to as having an open head, as compared with the closed-head type shown by the Bay of Biscay. It is evident that not only the character of the water, its temperature, currents, etc. differ in the two types, but also the quantity and character of the sediments, the closed-head type receiving the drainage of the land direct, together with the sediments brought in, while the open type receives only the finer sediments

which escape from the adjoining water body, besides the sediments brought in by lateral streams.

An example of the narrow type of deep funnel sea with an open head is seen in the Gulf of Aden (Fig. 436) which receives the outlet of the Red Sea, another mediterranean. Finally, there are shallow or epicontinental funnel seas, the most conspicuous example being the Bay of Fundy. This is also a narrow type, and this and its shallowness are responsible for the great range of the tides for which this water body is famous. (Compare with Estuary.)

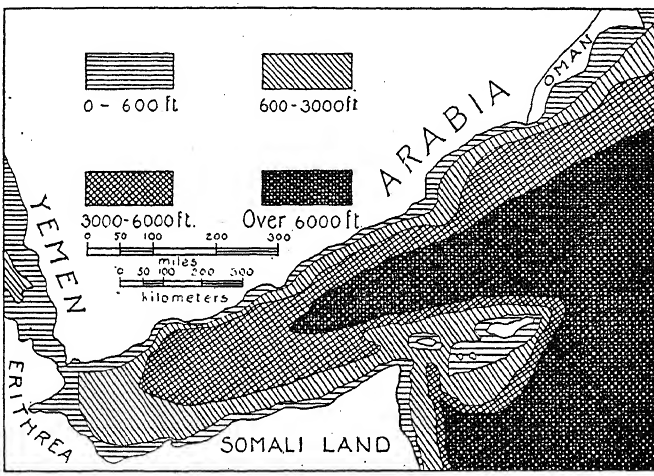


FIG. 436. — The Gulf of Aden, which exchanges its waters with the Red Sea. A narrow type of funnel-sea with open head. The continental shelf (*littoral zone*) is lined horizontally. The next two zones belong to the continental slope — the higher (600–3000 ft.) is the *typical bathyal zone* (diagonal lines); the next (3000–6000 ft., cross-lines) the *deeper bathyal zone*. Beyond this (below 6000 feet or 1000 fathoms, dark shading) is the *abyssal district*. (Compare with section, Fig. 438.)

Mediterraneans. — When the continental shelf or an inland portion of the continent is deeply excavated, but in such a manner that the deeper portion is everywhere surrounded by a higher rim, a *mediterranean sea* is produced. Such seas may also be formed by the dropping down of small blocks of the continental mass, or by very pronounced slow warping of a part of the continental shelf. A mediterranean sea, while truly intra-continental or within the land block, as is the case with the deep funnel sea, differs from the latter in having its bottom rise in all directions, while its outline

may vary from nearly circular to elongated oval or irregular. In all cases, however, there is a shallow outlet across the rim or there may be several such, these outlets leading to the open ocean (Gulf of Mexico) to a funnel sea (Roman Mediterranean or Red Sea) or to another mediterranean (Black Sea). Should the land rise, carrying the mediterranean with it, or should the sea-level sink, such a mediterranean sea will be converted into a lake, either without outlet, when the water remains salt, as in the case of the Caspian, or drained by a river (Lake Baikal, Lake Tanganyikà), in which case the water will generally become fresh from excess precipitation.

The type of the mediterraneans is the one generally so called (the Roman Mediterranean), which lies between Europe, Asia, and Africa. It is really a compound body, with several deep centers. The Red Sea is another example, being land-locked like the Roman, and opening into a funnel sea (Fig. 437). The Black Sea, on the other hand, is a very nearly enclosed water body, almost a lake. The Gulf of Mexico is a mediterranean with several openings across a ridge from which islands arise, and the Caribbean Sea is a mediterranean with a still more extensively submerged outer rim, as are Behring Sea and the Sea of Okhotsk in the northern Pacific. These are generally spoken of as marginal mediterraneans lying within the continental shelf.

The importance of mediterraneans lies in the fact that they have their own ranges of temperature and salinity, currents, and other characteristics, which are on the whole distinct from those of the neighboring oceans. The differences are, of course, more pronounced as the enclosure becomes more complete, until such types as the Black Sea, with practically stagnant deeper waters, are produced.

Most mediterraneans date their origin from long past geological time. They are not as old as the oceans, but many of them have existed during successive geological periods.

Epicontinental Seas

Epeiric Seas. — The shallow seas of an epicontinental character which lie within the land masses, such as the Baltic Sea and Hudson Bay, have come to be called epeiric seas (ἐπεῖρος, *epeiros*, a continent). Their depth seldom exceeds 50 or 100 fathoms (300–600 feet), and they are formed chiefly by a gentle down-warping of the land surface until it has passed below sea-level. Such seas are always connected with the oceans by shallow passages, the narrowness of which often prevents much change in level of the water body during tidal fluctuation of the open ocean. The salinity of the water, its temperature, and its currents are also dis-

tinct in such a water body. In the past many such epeiric seas existed where now is the dry land; indeed, such seas have often been replaced repeatedly by dry land. They are of extreme im-

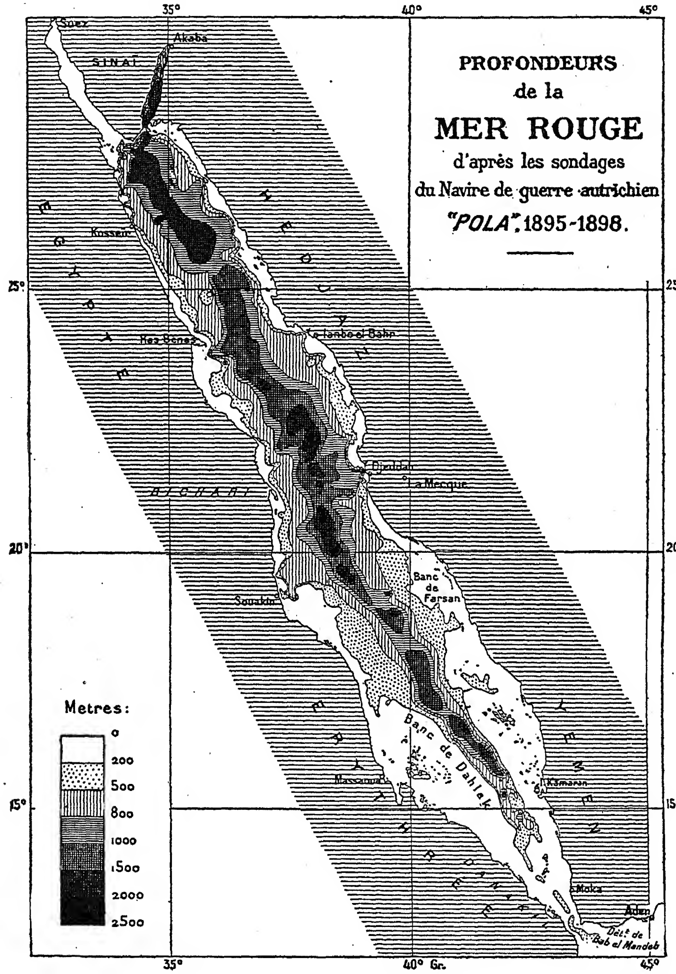


FIG. 437. — Map of the Red Sea, a mediterranean, showing the depths according to the soundings of the Austrian warship *Pola*, 1895–1898. (From Suess and de Margerie.) The continental shelf (*littoral zone*) is shown in white (0–200 meters, or roughly, 0–100 fathoms). The zones to a depth of 2000 meters (roughly 1000 fathoms) represent the continental slopes, while the deeper parts (in black) are the abyssal depths. Note that the Gulf of Suez is an epicontinental water-body, resting entirely upon the continental shelf, while the Gulf of Akaba is a subsidiary mediterranean.

portance in the history of older sediments. Marginal seas of this type situated on the continental shelf are the North Sea, Irish Sea, Tasmanian Sea, and others.

Geosynclines. — Along the base of high or mountainous land masses, there generally extends a belt of subsidence in which the bulk of the sediment brought from the mountains is deposited. This is the geosyncline. The rate of subsidence is usually constant, so that great thicknesses of material of uniform character may accumulate. Sometimes this material accumulates wholly above sea-level, as in the case of the north Indian geosyncline at the southern foot of the Himalayas already referred to (page 468). In other cases the sea has access to this trough, when great thicknesses of limestones or of other marine deposits may form. Not infrequently there is an alternation of continental and marine deposits, showing a variable rate of subsidence or a variable volume of sediment. In general the rate of subsidence and that of supply of material is evenly balanced, so that for a long time similar deposits may be formed at essentially the same elevation above, or depression beneath the sea-level. Such geosynclines of the past will be referred to at greater length under their proper periods in the section on historical geology.

Bathymetric Districts and Zones

The bathymetric districts and zones of the sea are those determined by the depth of water. As we have seen, this depth over the continental shelf does not exceed, as a rule, 100 fathoms (600 feet). This district and the shallow epeiric sea is illumined throughout by sunlight and agitated by waves, and constitutes the *littoral district* of the sea, though this term is restricted by some to the shore zone. This district naturally falls into two zones, (*a*) that of the shore between high and low tide (*shore zone*) and (*b*) that permanently submerged even at low water (*neritic zone*) (Fig. 438). Beyond the edge of the continental shelf the ocean floor slopes more rapidly to depths of about 1000 fathoms (6000 feet), and this constitutes the *bathyal district*, though some authorities limit this zone to depths of 500 fathoms. Beyond this lies the *abyssal* district, which comprises the larger area, between 1000 and 3000 fathoms (2400 and 5500 meters) and the smaller oceanic depressions or deeps, which descend to greater depths (30,000 feet or more).

The characteristic deposits of these several districts and zones will be considered in a later section of this chapter.

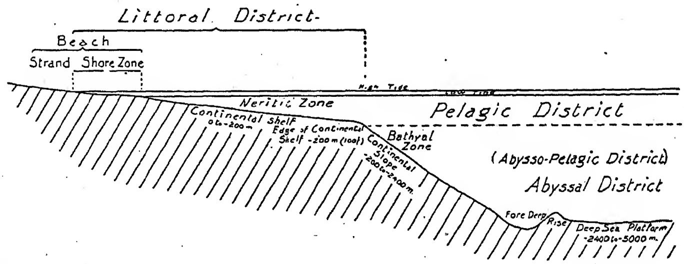


FIG. 438. — Diagrammatic cross-section of a part of the sea to show the several life-districts and the bathymetric zones. The edge of the continental shelf is marked by the 200-meter or 100-fathom line (approximately). That part of the sea which lies above the continental shelf and extends to high-water mark is called the *Littoral District*, this being divided into the *shore-zone* between high and low water and the *neritic zone* beyond that. From the edge of the continental shelf the "continental slope" descends to the deep sea (200 to 2400 meters, 100 to 1000 fathoms, roughly). The upper part of this, to a depth of 500 fathoms, is called the *bathyal zone* proper, the lower part the *deeper bathyal zone*. Above the floor of the deep sea lies the *abyssal district* of the ocean. Long, narrow depressions of the ocean floor parallel to the continents form the *fore-deeps*. The *pelagic district* is the upper part of the ocean to the depth to which sunlight penetrates — approximately 100 fathoms.

WAVES AND CURRENTS OF THE SEA

Waves. — There are many kinds of water waves, produced in a variety of ways; of these the waves produced by winds are the most important, because most common, though those produced by earthquakes and explosions, the so-called *tsunamis*, are often more destructive. Some of these will be noted in connection with our studies of earthquakes. The great waves known as the tides, two of which sweep around the earth in somewhat more than twenty-four hours, are of great importance as producers of oceanic currents, while the periodic rise and fall of the waters becomes significant along the shores, influencing not only the forces which modify such shores, but the life of the shallow sea as well.

The waves of the open ocean are due to a rotary movement of the particles of water (Fig. 439). Originally these are set in motion by the wind, but they are propagated beyond the zone of wind activity, so that even on calm days great waves or swells will be found in the ocean, far from their source of origin. As a result of

the rotary motion of the water particles the mass of the water rises and falls rhythmically, forming alternately the crest and the trough of the wave. The water particles move forward on the crest of the wave, downward on the back, backward in the trough,

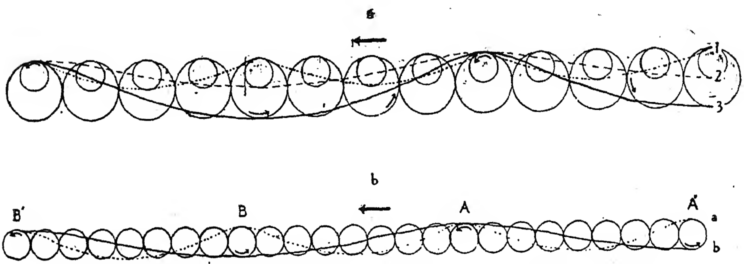


FIG. 439. — Diagram illustrating the formation of waves in the open ocean by a rotary motion of the water particles. As the particles revolve in the direction indicated by the small arrows, the wave form advances as shown by the heavy arrows. (From Grabau, *Principles of Stratigraphy.*)

and upward on the front of the wave. In water of limited depth, however, the path of the moving particles is an ellipse, with the major axis horizontal.

The *height* of the wave is measured by the vertical distance between the trough and the crest, and corresponds to the diameter of the orbit in which the water particles move. In the open ocean, wave heights from 5 to 15 feet are most common, but 20 or 40 feet is not an unusual height in storms, while heights of 45 to 50 feet have been recorded. The *length* of the wave is the horizontal distance from crest to crest. During stormy weather, in the open ocean, the wave length may be from 200 to 500 feet or over. When the wave reaches a length of a thousand feet or more, it is called a *swell* or *ground swell* and such waves have been found in exceptional cases to have a length of more than 2700 feet from crest to crest. The height and length of the wave depend upon the strength and continuity of the wind, and to some extent on other factors. The height of the wave decreases downward at a rate proportional to the wave length. If the diameter of the orbit of motion of the water particles is 20 feet, giving surface waves 20 feet high, and if the wave length is 400 feet, the diameter of the orbit of the water particles, at a depth of 400 feet, is $\frac{4}{10}$ of an inch.

Because of the regular rise and fall of the water in wave formation, the crest of the wave advances, although the water itself only rises and falls. The rapidity with which the wave crest travels is called the *velocity* of the wave, and this varies from 15 miles or less to 35 miles or more an hour and may be as high as 60 miles. For ocean waves of large size, the wave velocity is apt to be six or seven times as great as the orbital velocity of the water particles. For example, a wave 400 feet long and 15 feet high will have a velocity of about

45 feet per second (about 30 miles an hour), while the surface water particles will move round in their orbits at a speed of only $5\frac{1}{3}$ feet per second. The time taken by a crest to travel a wave length is called the *period* of the wave, and this, in storm waves, varies from 6 to 10 seconds or over. It corresponds to the time required for a particle to move around its orbit.

When great waves, by propagation, reach shallow water the free orbital movement of the water particles is interfered with, partly, as some hold, by friction upon the bottom, which retards the backward motion, but more especially because of the insufficient quantity of water to keep up the normal rotary motion. The wave becomes higher and shorter, its front steepens, while the crest arches forward (Fig. 440, *D*, *E*), and being unsupported

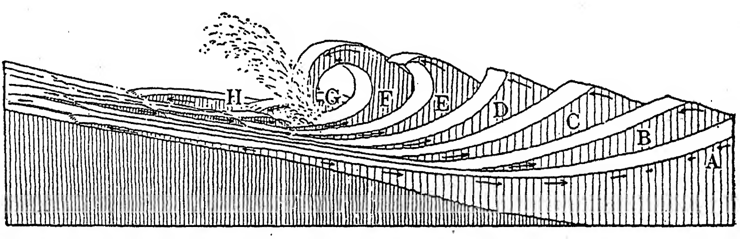


FIG. 440. — Diagram showing the development of the breaking wave (*A–G*), and the "swash" after breaking (*H*). (After Davis.) In general the wave breaks when the depth of water reckoned from the undisturbed sea-level is equal to the height of the crest above the trough.

by sufficient water in front of it, dashes downward with a roar, producing a breaking or combing wave (Fig. 440, *F*, *G*, Fig. 441). After the wave has broken, the water rushes up on the beach, forming the "swash," and returns seaward, carrying the sand and pebbles with it, the impact of the latter against one another often producing a loud rattling noise. In this manner rock fragments are rapidly worn into round pebbles (see p. 430).[1]

Waves of Translation. — The waves so far described are the ordinary ones, and are called *waves of oscillation.* There is, however, another kind, illustrated by the movement produced when still water is pushed into a mound by the shoving action of a boat. In that case a single prominent wave rolls forward over the surface of the water, there being no trough as in the oscillation wave. Such waves are called *waves of translation,* because the water particles rise and move forward to a new position as the wave form advances. When large waves

[1] For further details see A. W. Grabau, *Principles of Stratigraphy,* A. G. Seiler and Co., Chapter V, and D. W. Johnson, *Shore Processes and Shoreline Development,* John Wiley and Sons, 1919. Chapters I and II.

of oscillation break on a gently sloping shore far from land they give rise to a series of waves of translation which will advance up the beach, carrying the wrack of the sea landwards.

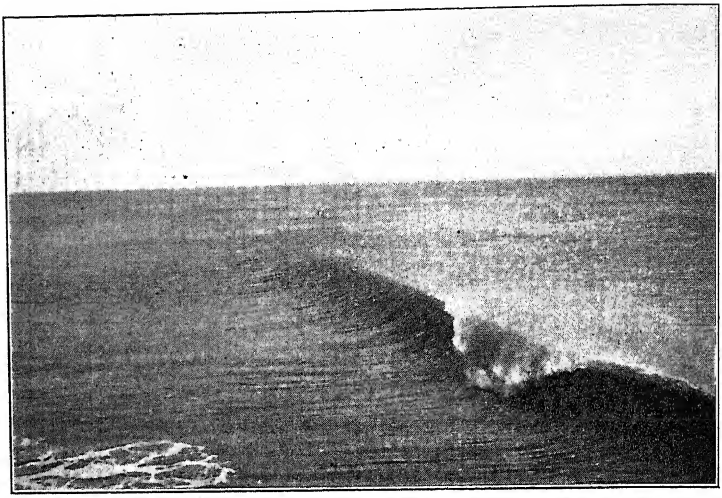


FIG. 441. — Combing wave, showing water completing orbital movement although insufficient in quantity to fill the wave form. Note the steep wave front in the foreground, and the decreasing steepness away from the comber in the distance. (Compare with Fig. 440.) (After D. W. Johnson, *Shore Processes*, etc. John Wiley and Sons.)

Wave Currents. — In shallow water, where the wave front is steepest, it will rush forward with a short, quick movement, while the return, or backward, motion is slower and of longer duration. The forward movement may be strong enough to carry large pebbles and cobblestones which the backward current is unable to move. Hence this coarser material will be carried landwards, while the finer material moves seawards. Coarse material dropped at a distance of 7 to 10 miles from land, where the water was from 10 to 20 fathoms deep, has been thrown on shore by storm waves, and even pig lead, from a vessel wrecked more than a mile from shore, has been cast upon the beach. Stones with large seaweeds or kelp attached to them are often cast ashore from the deeper water in which these seaweeds grow. Here a certain buoyancy is given to the stone by the seaweed. On steep coasts, however, the backward current or *undertow* may be very strong.

Beach Drift. — This term has been applied by D. W. Johnson to the transportation of material on the beach-slope, and parallel

to the shore, by current action due to waves which break obliquely upon the shore. In this case the *swash* advances obliquely up the slope of the beach, but the *back-wash*, moving under the control of gravity, tends to return directly down the steepest slope. Thus such material will zigzag along the shore, but the path of the particles will in reality be a series of parabolic curves, as shown in Fig. 442. These paths are larger for the finer than for the coarser material, the finer particle therefore traveling faster along the shore. The direction of the drift will depend on the direction of the prevailing winds, on the position of the greatest stretch of open water, since this largely determines the direction from which the larger waves will come, and on other factors. In some cases drift movement is in opposite directions from a given point. A similar movement of particles goes on in the off-shore deeper water region, where the material is moved to and fro on the bottom by the waves which advance parallel to the shore, but moves in a series of parabolic curves, if the wave advance is oblique. This is called *long-shore drifting.*

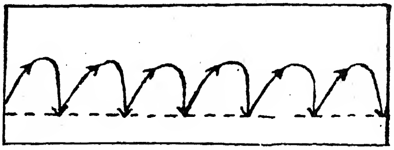


FIG. 442. — Diagram to illustrate the "zigzagging" of the particles in beach drift under the influence of oblique waves. The direction of movement is indicated by the arrows. The paths are parabolic curves. (After Johnson.)

Undertow and Long-shore Currents. — When, by the breaking of waves off shore, a succession of forward-moving water waves (waves of translation) is formed, the water will be piled up on the shore, above the normal level of the sea, and has to escape either seaward along the bottom or parallel to the shore. In the first case it forms the *undertow*, in the second the *long-shore current.* The undertow is especially marked in regions of steep off-shore bottom, and deep water close to shore, and further, where broad zones of waves strike the shore at right angles. The long-shore current is best developed where the waves strike the shores obliquely, and where the bottom shallows gradually.

Tidal Currents. — Under the influence of the attraction of the moon and, to a lesser degree, that of the sun, the water of the sea rises into two elevations on opposite sides of the earth, and these would sweep around the earth as two great continuous tidal-waves, were it not for the presence of the continents. Twice each month,

at new moon and at full moon, the tides are exceptionally high, owing to the relative position of the sun and moon at such times, when they exert a combined influence of the same character upon the waters. Such tides are called *Spring Tides*. Twice a month also, at the period of the first quarter and last quarter of the moon, the interval between high and low water is at its lowest, since at such times the moon and sun act in contrary direction upon the waters, each tending to neutralize the force of attraction of the other. This constitutes the *Neap Tides*.

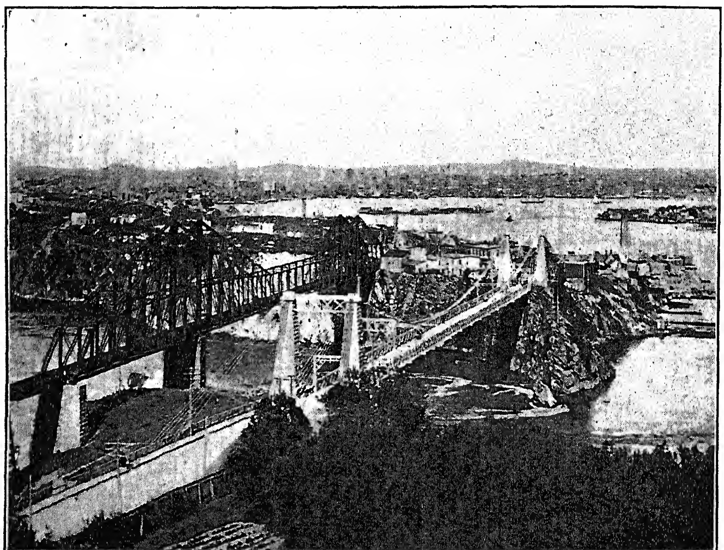


FIG. 443. — Reversible Falls, St. John, N. B. High tide. Water pouring westward into the harbor.

At a given point, the crest of the tidal wave arrives at intervals of 12 hours and 26 minutes. This produces the *flood-tide*. Six hours and thirteen minutes later the trough of the tidal wave replaces the crest, and low water or *ebb-tide* results. Because of the interference of the lands, the tidal wave is retarded and the time of high or low tide may differ widely from that of neighboring regions, though the interval remains the same. It may even happen that a low tide from one direction meets a high tide from another, as at Hellgate, where the high tide, entering from New York Harbor, arrives simultaneously with a low tide approaching through Long Island Sound, while six hours later the reverse is true. The strong tidal disturbances of the Straits of Dover, experienced by all who have made the crossing, are due to the interferences of tides arriving, the one from the North Sea, the other from the Atlantic

through the Channel. The famous " Scylla " and " Charybdis " in the Straits of Messina are whirlpools, produced by the meeting of tides from opposite directions, and a similar phenomenon is noted on the coast of Massachusetts at Woods Hole.

Where the tides pass through narrow channels, powerful and dangerous currents are generated, and these may affect the bottom, even at considerable depth, by sweeping away all loose material and depositing it elsewhere. When the tides are compressed in

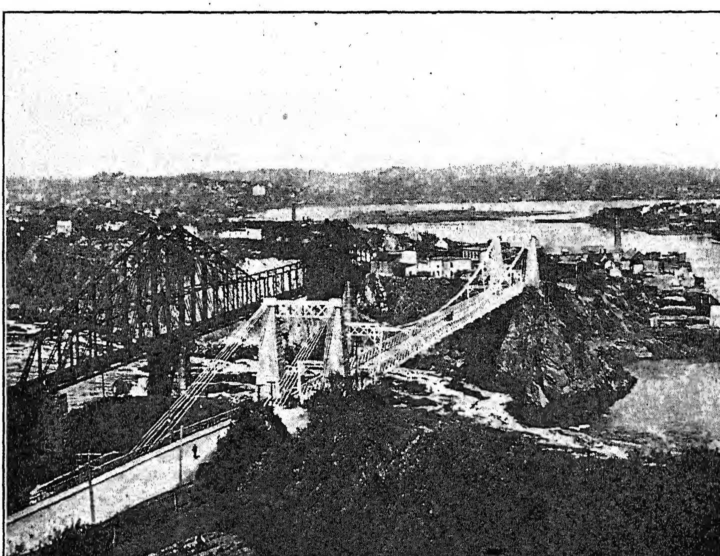


FIG. 444. — Reversible Falls, St. John, N. B. Low tide. Water pouring from the harbor, flowing eastward.

narrow inlets, such as the Bay of Fundy, they may pile up near the head of the bay to a height of 30 or 40 feet and in exceptional cases to a height of 70 feet. The rapidly rising tide of this bay pours into St. John Harbor through a narrow inlet, the surface of this basin rising more slowly than that of the ocean without, on account of the narrowness of the passage. Conversely, the tide in the Bay of Fundy falls more rapidly than the water can pour out from St. John Harbor. Hence a reversible fall is produced, facing inward when the ocean is highest and outward when it is lowest. The maximum difference of elevation of the water surfaces is nearly 10 feet (Figs. 443, 444). Related phe-

nomena exist upon the coast of Massachusetts. The influence of the tidal currents is very marked in estuaries and will be referred to later.

Planetary Currents. — These represent the great oceanic circulation set in motion primarily by the planetary winds and modified by the rotation of the earth, the configuration of the lands, and by other factors. In an ideal ocean of symmetrical form, reaching from pole to pole, and covering a meridional distance of 90°, the circulation would be essentially like that shown in Fig. 445.

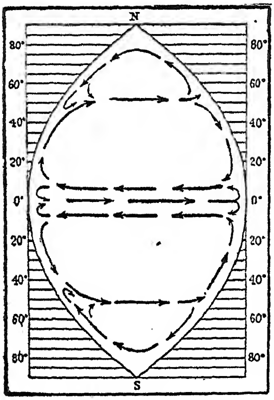


FIG. 445. — Diagram showing the circulation in an ideal ocean extending from pole to pole and covering one fourth the circumference of the earth (90°). (After Krümmel.)

On both sides of the equator, at 10° north and south latitudes, the equatorial stream would flow westward under the influence of the easterly winds. On approaching the western shore it would bend northward and southward, respectively, crossing eastward again in latitudes 50° north and south, and returning to the equatorial region on the eastern side. This constitutes the principal circulation. Arctic and antarctic currents would also exist, flowing as indicated in the diagram. Between the two westward-flowing equatorial currents is an eastward-flowing equatorial counter-current, which is, however, much weaker. The equatorial currents are warm and they impart their heat to the westerly shores where they turn, respectively, north and south, while the return currents are cooled in their northerly and southerly passages.

The outline of the continents is responsible for marked deflections of the currents, while the position of the equatorial currents is also modified by the shifting of the heat equator. The south-equatorial current crosses the Atlantic with an average velocity in June, July, and August of from 1.6 to 1.8 km. per hour. Striking the projecting point of South America, at Cape St. Roque, it divides, one arm passing southward to become the Brazil current, while the other (northern) unites with the north-equatorial current to produce the Guiana current, which later becomes the Gulf Stream. This makes the circuit of the Gulf of Mexico and escapes by the narrow passage between Cuba and Florida (Fig. 225, p. 301). It turns northward between Florida and the Bahama banks, crossing

the Atlantic approximately in latitude 40° N. Its further course may be noted by reference to a map of these currents in any good atlas. At the Florida Straits, the average velocity is 5.55 km. per hour, but rises to 9 km. per hour in the warmer season. The velocity rapidly decreases northward, and where the Gulf Stream crosses the Atlantic, it averages not much over 1 km. per hour. In the center of the great North Atlantic eddy, the ocean is relatively quiet, and is filled with the floating sea-weed *Sargassum*. This region has, therefore, become known as the *Sargasso Sea*.[1]

It should be noted, however, that these great oceanic currents seldom come near the coast, or if they do, their effect is overcome by other local currents. This is true even of the Gulf Stream in the Florida Straits, which is separated from the land by another and slower current moving in the opposite direction.

Other Currents. — Besides those described there are other currents in the sea and in great lakes, most notable among which are those produced by winds which blow steadily in a given direction. These currents are often of great importance, especially in enclosed or nearly enclosed water bodies. Other currents are due to difference in salinity of the waters, to convection, to rivers entering the sea or lakes, and to other causes.[2]

Sources of Clastic Sediments Deposited in the Sea

The clastic material which finds its final resting place in the sea is derived from a number of sources, and brought to it in a variety of ways. The principal of these are as follows:

Land-derived or Terrigenous Material

Clastic material derived from the land is called terrigenous (earth-born); and this may be the product of weathering or of mechanical erosion as already outlined in an earlier chapter (p. 424). This material is supplied to the sea: (*a*) by rivers, glaciers, icebergs, etc. which bring it from the land, (*b*) by the wind, often from great distances, (*c*) by erosion of the seashore by the waves, and (*d*) by the scouring action of the oceanic currents.

[1] For further details, and for description of currents in the other oceans, see the author's *Principles of Stratigraphy*, pp. 231–244.

[2] For a discussion of these see Johnson, D. W., *Shore Processes*, etc., chapter iii.

Clastic Material Derived from Organic or Chemical Deposits in the Sea

Under this heading belongs the clastic material which is torn from structures built in the sea from material formerly in solution; namely, coral reefs, shell deposits, and the like, as well as from chemical deposits in the sea. Of these the coral reefs are by far the most important sources of clastic material, this being of course wholly composed of carbonate of lime with some magnesia. The destructive work is performed by the waves and by animals which feed upon the reef-building organisms and crush their calcareous structures (see *ante*, p. 437).

Clastic Material of Subcrustal Origin

Explosive eruptions of submarine volcanoes furnish clastic material to the waves and currents, this being often of considerable amount. Lava streams poured out upon the sea bottom will, if they come within the reach of the waves, be subject to their attack and so furnish clastic material for other sediments.

Material of Meteoric Origin

Meteoric dust and stones from spaces outside of our solar system frequently reach the earth, and probably fall into the sea in no inconsiderable quantities. These are incorporated in all kinds of marine sediments.

Transportation and Sorting of Clastic Material in the Sea

The material furnished to the waves and currents of the sea by the various agencies above enumerated may be transported by them over wide areas before it finally comes to rest. The work of the waves consists mainly in stirring up the material so as to place it in the best position, that of suspension, for the currents to transport it. In general, such transportation is most effective in the shore-zone of the littoral district and in the shallow part of the submerged zone, but it is also effective in the deeper part of that zone. On the shore the chief currents are the *long-shore current*, which carries the material more or less parallel to the coast, and the *undertow*, which is the return current on the bottom, inaugurated upon the breaking of a wave against the shore. This current tends to

carry the material farther out to sea. There are, however, also other bottom currents in the deeper parts of the submerged zone which may do no inconsiderable amount of transportation. Chief among these are probably the tidal currents, though others, set in motion by the normal circulation of the ocean (the great oceanic or planetary currents), are also active.

Both waves and currents perform a certain amount of sorting of the material supplied; the finer-grained the material the longer will it be kept in suspension by the waves and the farther away will it be carried by the currents. Sorting of clastic material is best accomplished when there is vigorous wave action accompanied by strong undertow, and when the volume of sediment supplied is moderate. On the other hand, if large quantities of sediment are furnished to the waves, only a moderate amount of sorting is effected. Where strong currents support material in suspension for a long period of time, picking it up again repeatedly after dropping it, a considerable amount of sorting may be produced. Such sorting will be according to both size of grain and character of material, and as a result pure quartz sands will be found in some localities, sands largely composed of heavy minerals, such as garnet and magnetite, in others, and muds in still other localities. By mutual attrition of the grains, a considerable amount of rounding is produced, but it must be recognized that such rounding is seldom or never as perfect, nor the sorting according to size of grain as complete, as is the case with wind-transported material. As a result, the sands of the sea-beach generally consist of commingled coarser and finer grains, most of them subangular, — this angularity, and the presence of water held by capillary attraction between the grains, serving to bind them into a compact mass. This, in some sections, results in the production of so firm a floor at low tide that it forms a favorite region for the trials of speed of high-power racing machines. (See Fig. 357, p. 431.)

Fine sediments may be carried out to sea for hundreds of miles, and this accounts for the fact that the entire surface of the continental shelf is covered with sand, while the mud-line begins, as a rule, at the edge of the shelf and continues over the bathyal district. Terrigenous muds are probably seldom carried to the deeper sea, where volcanic or meteoric matter forms the chief clastic sediment, together with the inorganic matter derived from the structures of organisms.

In such regions, however, rafted material may form important deposits. We have already referred to the ice-rafted material which forms some submarine banks and which has been brought there by floating icebergs. Materials attached to or held by the roots of floating trees and other vegetation from the land may also be distributed widely. Thus leaves of land plants are frequently dredged in deep water, and tree trunks from the tropical rivers of America have been carried by the Gulf Stream to the Arctic regions where they have been cast ashore on far-distant northern lands and islands.

Types of Clastic Deposits in the Sea

Deposits in the Shore Zone

The Beach. — The sea beaches of the modern oceans consist very largely of sand. Even where the sea is faced by a rocky cliff

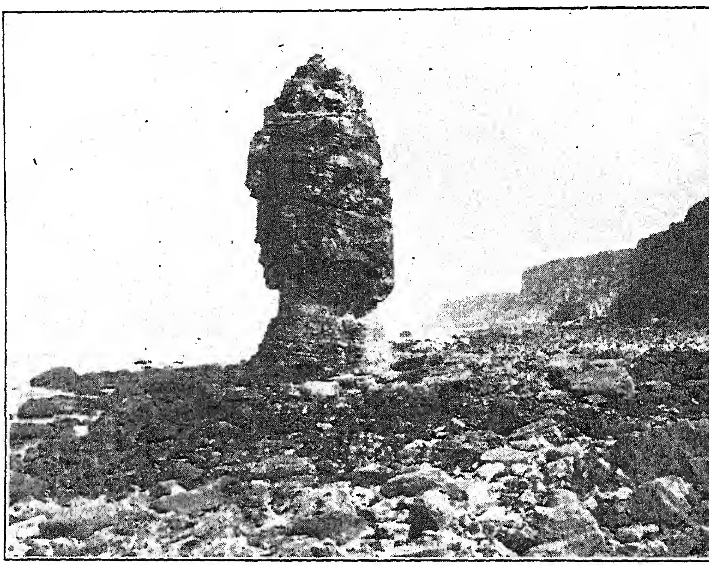


Fig. 446. — Rock fragment beach at the foot of a rocky cliff, a portion of which remains in the foreground as a marine "stack" or chimney, coast of France. The beach here forms a bench and the coast topography is young. (From Johnson's *Shore Processes*; John Wiley and Sons.)

which is actively undergoing erosion by the waves at the base and by weathering at the top, coarse materials such as large blocks, boulders, and pebbles are restricted to a relatively narrow zone, beyond which the material of the sea-bottom is sand (see Fig. 356 *b*, p. 430). Where cliffs are undermined by the waves, huge blocks often cover

the beach at the foot of the cliff, but these will undergo gradual destruction in time (Fig. 446). Sometimes, however, the conditions are favorable for their preservation, the spaces between them being filled by finer material and the whole becoming bound together into rock. Such rock formed during the Jurassic period of the earth's history, and carrying blocks of stone twenty feet in length, is found exposed on the eastern coast of Scotland, where the blocks had accumulated much as they accumulate in parts of that region to-day. Mingled with the material of the coarse fragments of rock are heads of corals and other organic remains, the larger ones generally waterworn.

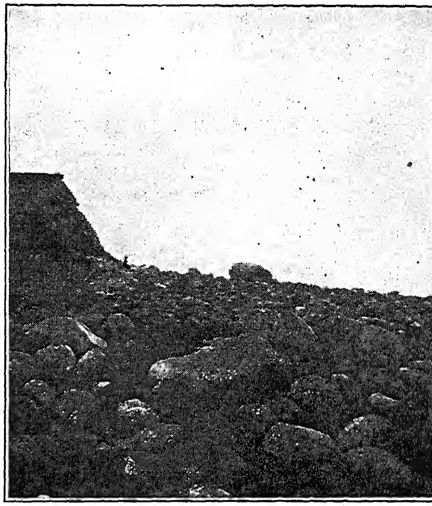


FIG. 447. — Section of Grover's Cliff, near Winthrop, Mass., showing erosion of drumlin by waves and the formation of a boulder beach from the larger stones of the drumlin material. These boulders are partly overgrown with seaweeds which give them a certain buoyancy at high tide. This and the shore-ice serves to arrange these rocks into a solidly packed pavement of boulders. (Photo by the author.)

Boulders are also characteristic of the coast where old glacial moraines, either terminal or ground moraines, are exposed to the attack of the waves (Fig. 447). At Woods Hole and along the shores of the Elizabeth Islands group on the southeastern coast of Massachusetts, many good sections of the terminal moraines are exposed, and huge boulders are strewn over the beach for some distance out from the shore. At several places in Boston Bay drumlins have been cut into by the sea and great accumulations of boulders form the shore zone (Fig. 447). These boulders are often overgrown with seaweeds, which sometimes act as a buoying agent making possible their movement by the waves even on the gently sloping coast. This buoyant power of seaweeds together with that of shore ice in winter has enabled the waves to arrange the boulders in close juxta-

position so as to produce at low tide the appearance of a boulder pavement. On the gently sloping portion of the North Sea coast of Scotland, such closely arranged boulders are not only thickly overgrown with seaweeds, but also serve the limpets and other shell-bearing mollusks, and even the soft-bodied sea anemones, as a place of attachment. Where the coast slopes more steeply, the boulders are moved by the strong waves, and here all organisms are ground up and the boulders appear barren. If strong waves break upon the shore, they often effect the formation of terraces with gently sloping upper surfaces and steeper seaward faces. These terraces are more common where the rock fragments are relatively small, as of the size of a man's fist, and in that case the fragments are mostly worn into round, smooth cobble-stones. Such terraces of cobble-stones are shown along some portions of the Massachusetts coast as at Marblehead (Fig. 448 *a*), and also along the borders of some of our Great Lakes. They are also characteristic of many parts of the Scottish and other coasts (Fig. 448 *b*).

Fig. 448 *a*. — Cobble-stone terrace on the coast of Marblehead, Mass. Note the flat summit and the steep frontal slope of the terrace. (Photo by the author.)

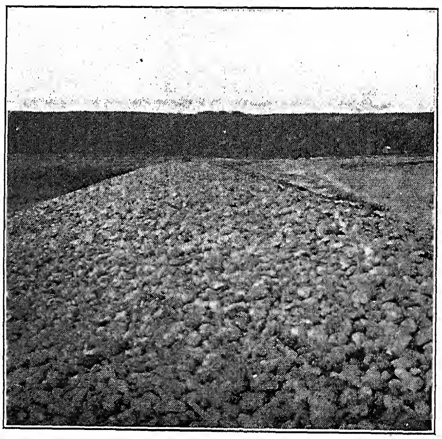


Fig. 448 *b*. — Barrier beach, or cobble terrace, North Sea Coast of Scotland. (Photo by M. I. Goldman.)

Where cobble and pebble beaches have been raised by recent earth movements, as in many places along the Scottish and other coasts, these beach deposits are often full of the shells of shore mollusks, such as the limpets, as well as the hard parts of other marine organisms. When consolidated they will form a fossiliferous conglomerate. Examples of such rock are known from many older geological formations.

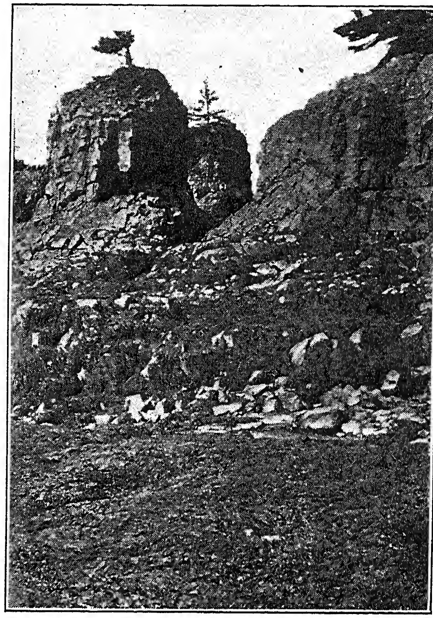


FIG. 449. — Low tide near the head of the Bay of Fundy. The rocks and boulders are overgrown with seaweeds (Fucus, etc.), and these are exposed between tides. The stacks in the view are the result of marine erosion at high tide. (Photo by M. O'Connell.)

Sections of boulder beaches and terraces are rarely seen, but it is apparent that their structure must be an irregular one, with perhaps the development of coarse cross-bedding. Where rivers descend from high mountains near the coast, great beds of "shingle" or pebble beaches are formed along the coast, as is shown along the base of the Maritime Alps between Toulon and Genoa, and especially near Nice, on the coast of the Mediterranean. A great part of the pebbles is, however, swept into the Mediterranean, which in some sections, as at Nice, drops off rapidly to a depth of 2000 feet at a few hundred yards from the beach. North of Messina on Sicily, a torrential river carries annually vast masses of granite pebbles into the sea.

Sand beaches, on the other hand, are commonly broad and flat, sloping gently toward the water and under it. Here and there the surface will be characterized by ripple marks and the peculiar lines which are left on flat shores by each little wavelet, the extent of which they outline. Shells of mollusks and often those of foraminiferans, and the remains of crustaceans, fish, and other animals

are buried in the sand, sometimes in large numbers, sometimes as scattered individuals. Frequently the currents and waves collect the shells in protected embayments, and there they accumulate in large quantities and may become embedded as shell layers in the sands. On the coast of Florida such shell layers of lenticular form are inclosed in the beach sand, and because of their consolidation into a shell rock, or coquina, they form limestone shelves at the water's edge. A number of these have been described by J. F. Kemp.

One of the most remarkable beaches in existence, is found in the Bay of Fundy, where the rise of the tide is unusual, being commonly from 30 to 40 feet or over, as noted previously (Fig. 449). Where

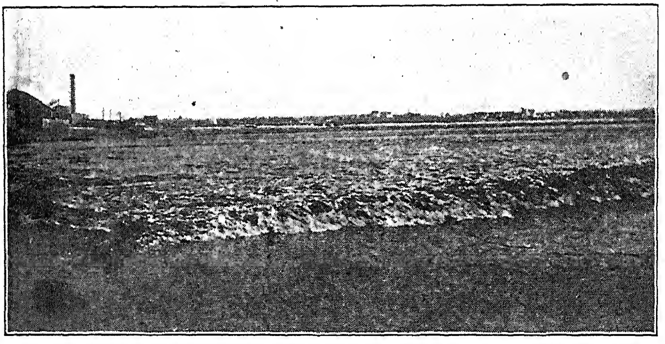


FIG. 450. — The tidal-bore at St. John, N. B. The water rushes up the river valley, presenting a steep front and producing a roaring sound as of violent rapids.

the beach is gently sloping, as in the Basin of Minas, the water recedes for miles, laying bare huge flats of red mud and sand, which were derived from the erosion of the older red beds of the shore. Across these flats, the streams and retreating tidal waters cut channels of varying complexity, with rill marks upon their borders, while raindrop impressions are found wherever a shower strikes the drying mud. Worms crawl over the surface or move just beneath it, forming characteristic tracks; shells of dead mollusks are left stranded upon the red mud surface, and the remains of many other organisms are strewn about. When the tide returns, it sweeps across the flat surface with surprising speed and enters the narrow river channels in the form of a steep frontal wave called the "bore," which rushes up the river with the noise and the rapidity of a breaking wave upon the sea-shore (Fig. 450). The

mud of the bottom is stirred up, and the water is thick with sediment which later, as the agitation of the water subsides, settles upon the bottom, covering any structure not destroyed by its mad shoreward rush.

Here we have a good example of the reworking of red sands and muds derived by erosion of older red beds, which themselves were a continental deposit. These reworked beds will possess the characters of a seashore deposit, with its peculiar features impressed upon it. Among the older rock series of the earth's crust, there are several such red stratified formations with marine features and with characters which appear in all respects to conform to the sediments now

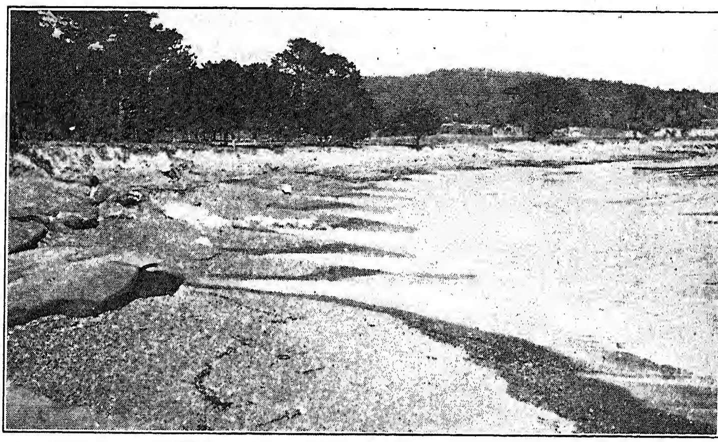


FIG. 451. — Beach cusps on shore lines of Carmel Bay, Monterey County, California. Photo by W. S. Cooper. (Courtesy of D. W. Johnson.)

forming in parts of the Bay of Fundy. These can confidently be regarded as ancient products of activities similar to those visible in Nova Scotia to-day. One of the best known of these is the so-called Medina sandstone, which was formerly extensively quarried in western New York, and has been used widely for flagstone sidewalks. On this rock, not only solid ripple marks are seen (often recognizable in the older sidewalks of Buffalo, Rochester, and other cities where this rock is used for flagstones), but beautifully preserved wave marks, shell-protected sand ridges, and other characteristic beach features are found. Here, too, are preserved, in some cases, the beach cusps similar to those formed on modern beaches and next to be described. The beach here fossilized was a very ancient one, belonging to the interior or epeiric seas which covered North America in Silurian time.

Beach Cusps and Ripple Marks. — When the waves strike the shore directly, the front of the beach will commonly become excavated into a series of scallops or concavities with sharp ridges or

cusps between them (Fig. 451). These beach cusps project at right angles from the front of the beach and form a series of sand or pebble ridges of triangular outline with the base of the triangle on the shoreward, and the apex on the water side. They vary greatly in their distance apart, according to the size of the waves which produce them, but in any given series they have a relatively uniform spacing. "Where the waves are about an inch in height, the cusps are from 3 to 9 inches apart; where the waves are from one and a half to two and a half feet high, they are 30 to 60

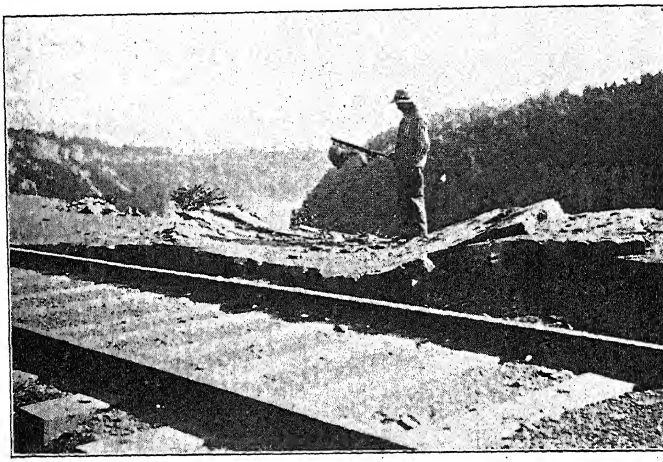


Fig. 452. — Remnant of the concavity between two beach-cusps, preserved because of the consolidation of the old beach sand into a solid rock. This rock forms a part of the Medina series (Whirlpool sandstone) of the Silurian, and the position of the cusps indicates that the old Medina shore-line was approximately parallel to the railroad track of to-day. Niagara gorge. (Photo by G. K. Gilbert; from U. S. G. S.)

feet apart, while large storm waves build cusps 100 feet or more apart" (Johnson). What appear to be fossil beach cusps have been found in ancient beach-formed sandstones, in one of which (Medina sandstone of Silurian age, already referred to), exposed in the gorge of Niagara below the whirlpool, they are wonderfully well preserved (Fig. 452). Ripple marks are not common on open beaches, but in protected areas they are often well developed (Fig. 453). They are of the asymmetrical or current ripple type. (See further, p. 550.)

It is difficult to get at the internal structure of modern beaches, but in a few cases, where sections are exposed by wave cutting, an irregular but strongly-marked stratification is seen. The layers

are essentially horizontal and in some cases very perfect, while in others a certain amount of pinching out and overlapping of the ends of layers is seen. Cross-bedding on a large scale is rarely indicated, though that due to ripple marks, on a scale of inches, is not uncommon.

Fig. 453. — Beach near St. Monans, east coast of Scotland, showing current ripple marks in protected embayment of shore with numerous worn castings in the troughs. Dr. Benjamin Peach of the Scottish Geological Survey on the right. (M. I. Goldman photo.)

The Bar. — On a gently sloping coast the large waves commonly break at a distance from shore, often several miles from it, where the depth is such that the waters in their rotary motion just strike the bottom.

The breaking wave (Fig. 441) digs up the sand of the sea-bottom and hurls it forward, depositing it in front of the line of breakers, and by repeated work of this kind builds up a sand ridge or *bar* parallel to the line of the breaking wave and therefore in general parallel to the shore. When this bar has been built so high that at low tide it is exposed, sand dunes are likely to be formed upon it, and it becomes a barrier beach with a lagoon between it and the land as already outlined (page 330).

When the emerged bar or barrier beach is attached at one end to a projecting headland of sand or gravel, a large amount of material is furnished by the erosion of this headland. If this material is carried by the long-shore current parallel to and along the shore of the barrier beach, it tends to fill up the tidal inlets or breaks in the continuity of this beach. The result is that barrier beaches are always most continuous in those portions which spring from the sand-supplying headlands, becoming less so away from this. On the south shore of Long Island the great bar known as Fire Island Beach extends unbroken for more than

40 miles southwestward, while the three main barrier beaches farther west, which are not joined to headlands, are each less than 10 miles in length. Rockaway Beach, still farther west, also springs from a sand-supplying headland, and is rapidly growing in length, as shown in the maps (Fig. 457 *b*). When the beaches are shorter, that is, when the tidal inlets across the bar are more numerous, the normal condition for the growth of salt-water vegetation is best developed, and the lagoon is converted into a marsh, as previously described (p. 331). The protected lagoon behind the continuous bar, however, favors such growth to a lesser degree, chiefly because there is less rapid filling of the lagoon to the required depth for the growth of such plants, and also because this portion is often freshened by the inpouring of stream-waters. Hence the protected lagoon will remain open for a longer time. Conditions of this type also exist on the New Jersey and other coasts characterized by barrier beaches.

From the way in which the sands are piled up to form the bar, we may infer that its internal structure is very irregular, and that if a section were cut across it, an irregular cross-bedded structure would appear. Such a bar may, under favorable conditions, harden into a rock by cementation of its sand grains by lime or other substance, as happens on the coast of Brazil, where wave-formed bars form lines of solid "stone reefs" as they are called. Again, near the shore such a bar may be preserved by changes in sea-level, which leave it submerged and allow the formation of other sediments over it. When such a bar is changed to rock, this rock will exhibit in its structure the characteristic oblique bedding which is probably not very different in general appearance from the cross-bedding of wind-laid sediments.

As has been briefly outlined in a previous chapter (p. 332), the off-shore bar is not a stationary structure, but is subject to continued wave attack, for now that the ocean bottom has been sufficiently deepened in front of the bar by the excavation of the sand from which that bar was built (see Fig. 273, p. 330), the waves will break close to the shore of the bar and will therefore be able to erode it. Such erosion is more active of course where little material is supplied by the long-shore currents, and therefore in those portions of the bar which are farthest away from the sand-supplying headlands. If the lagoon has been transformed into a peat marsh (see p. 332), the shore dunes will advance over it, as the bar is being eroded, the sand compressing the peat by its weight. The barrier beach thus migrates shoreward in the

course of time. As the erosion on the seaward side continues, the peat-beds of the lagoon will be reached, and become exposed upon the shore at low tide. Such peat exposures are seen in a number of places upon the Atlantic coast, those most readily accessible from New York being just east of Fort Hamilton on the Long Island coast. Eventually, with continued erosion the

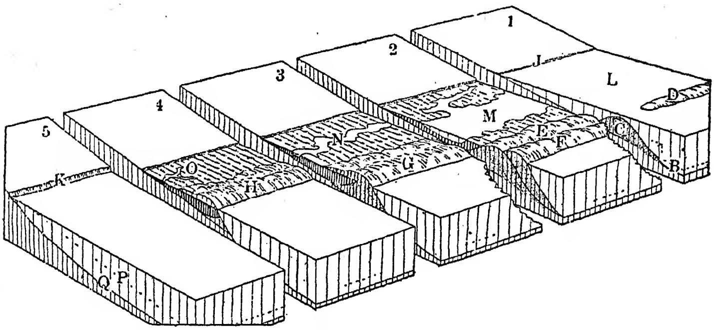


FIG. 454. — Diagram illustrating the development, migration, and complete destruction of an off-shore bar and the lagoon deposits behind it. (After Davis.) 1. The bar just beginning to emerge, the lagoon open, and the shore of the mainland marked by a small erosion scarp or "nip"; 2. Completion of the barrier-beach and formation of salt marsh, with lagoon in the center; 3. Advance of the beach and dunes on the marsh with progressive erosion of the bar on the seaward side. The lagoon is now converted into a salt marsh intersected by a tidal stream N; 4. Complete destruction by the waves and currents of the original bar — advance of the beach and dunes over the marsh which has now become exposed upon the shore; 5. Final stage, showing complete destruction of the lagoon and its deposits, and the advance of the deeper water to the original shore, which is now being cliffed by the waves. The dotted line shows the original slope of the sea-bottom.

entire lagoonal deposit is cut away, and the sea is able to attack the mainland with the full force of its waves, which it was unable to do before the building of the bar because of the shallowness of the water near shore. The various stages in the building and migration of the bar and barrier beach are shown in the preceding diagram (Fig. 454).

Bars of this type are found to form a more or less continuous series along the Atlantic coast of North America from Long Island southward (Fig. 455, p. 540). They also occur on the Massachusetts coast, and are characteristic of many other coasts as well. On their seaward side they exhibit all the normal features of the beach. Because of the exposed character of the beaches, the winter

storms often effect a considerable amount of cutting, sometimes doing much damage to buildings and other structures (Fig. 456). The bars of the Baltic, and the movements of the sand dunes upon them have been described in a previous chapter (p. 445, Figs. 364 *a*, *b*).

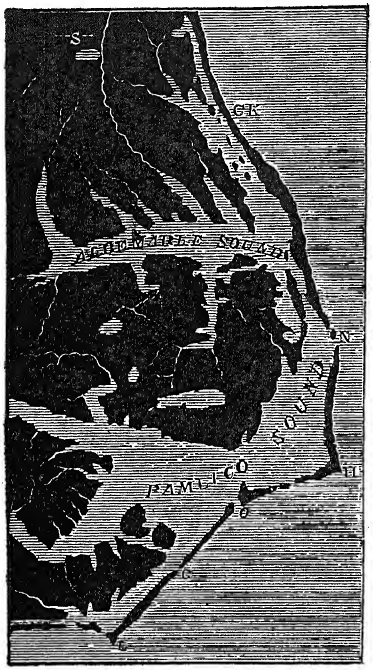


FIG. 455. — Map of the coast of North Carolina, showing a coast with drowned river valleys, modified by the subsequent formation of off-shore bars and barrier beaches, built at a great distance from shore because of the gently sloping character of the subcoastal plain. *CK*, Corrituck bar and lagoon; *N*, New inlet; *H*, Cape Hatteras; *O*, Ocracoke Inlet; *L*, Cape Lookout. The sharp angle at which the bars meet to form Cape Hatteras has been explained by some as due to deposition of débris derived from both north and south, in a triangle of quiet water between two adjacent circling currents, while others have suggested the influence of an initial projecting shore line or shoal.

The Sand-spit. — The usual on-shore movement of the waves is seldom direct, but nearly always more or less oblique. As a result, the sands (and pebbles), moved up the beach by the swash or the breaking wave itself, proceed in an oblique direction, but the undertow carries this material back at right angles to the shore line. In consequence, the material moves in a zigzag fashion along the beach, here in one direction, there in another, according to the conformation of the shore. (See p. 523.) If the shore recedes abruptly into the land as at an inlet, the moving sands reach water too deep for their further progress, and they come to a temporary rest. By constant piling up of such sands, etc., a tongue begins to project into the water, and this continues to grow in length until a sand-spit of considerable extent is formed. Where strong tidal or wind-driven shore currents exist, they greatly aid in the transportation of the material along the shore. Sand-spits thus represent a prolongation of a beach into the deeper water where

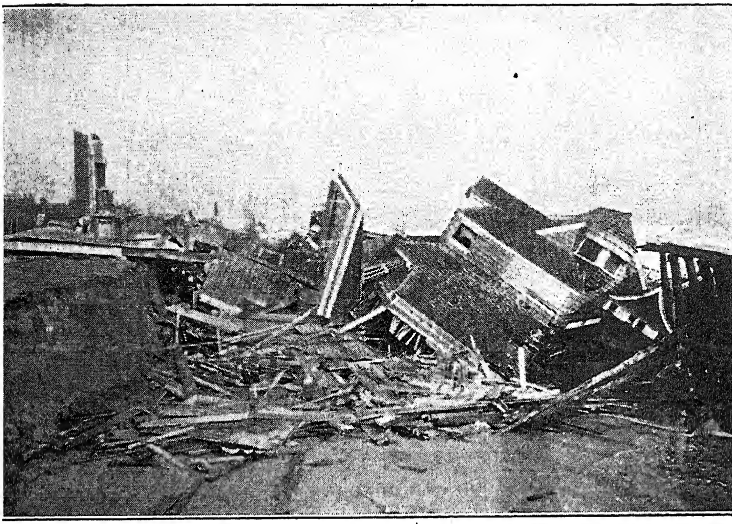


FIG. 456. — Ruins of summer residence at North Long Branch, New Jersey. (Photo by D. W. Johnson.)

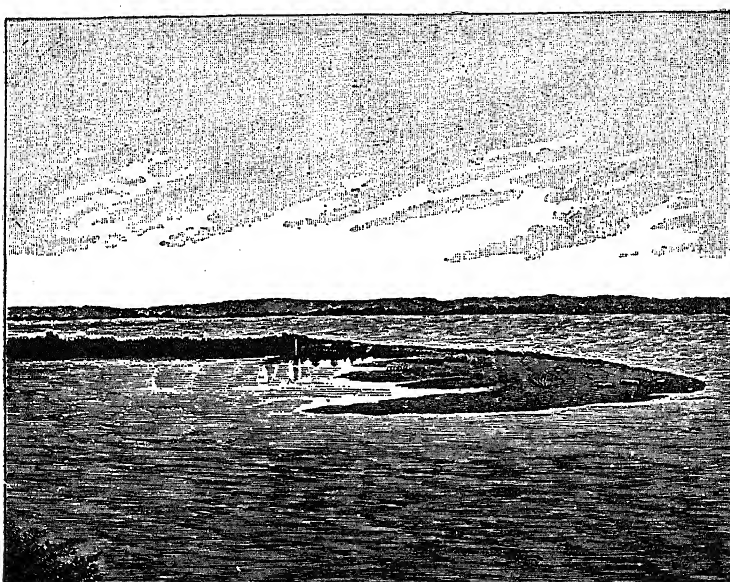
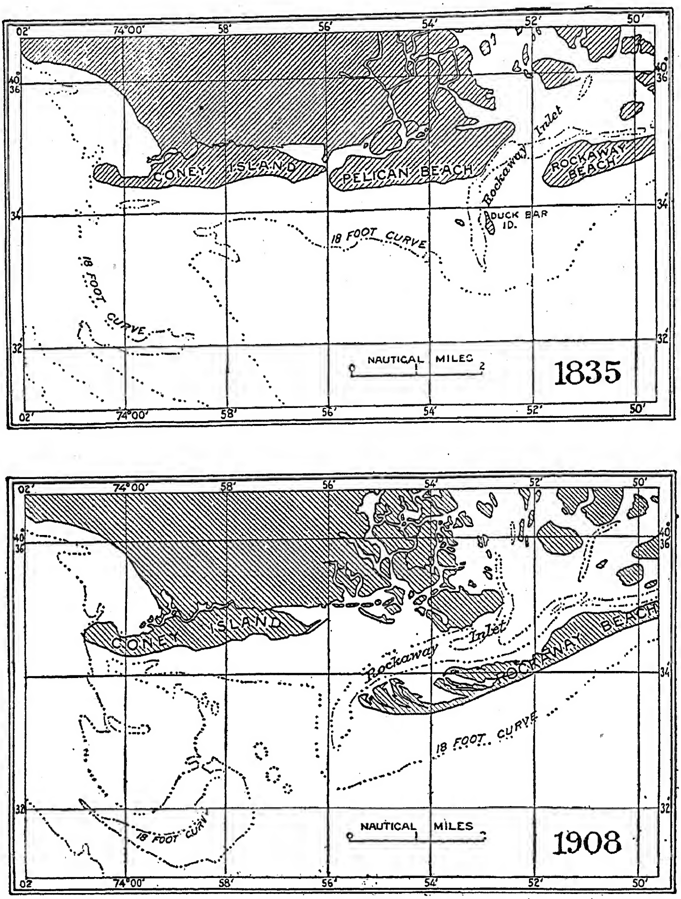


FIG. 457 *a*. — A sand-spit, Traverse Bay, Lake Michigan. (Shaler.)



Charts from George R. Putnam.

FIG 457 *b*. — Westward growth of the compound sand-spit of Rockaway Beach between the years 1835 and 1908 (*National Geographic Magazine*). In 1889 the curved spit near meridian 73° 54′ was the westernmost, although at that time it was broader and extended across the meridian. It has suffered erosion during the formation of the later spits. The outermost spit has been built since 1905. Between 1908 and 1912 the change has been very slight. The influences of the tidal current through Rockaway inlet in producing the curvature of the spits is well shown.

the shore has receded. According to circumstances and the direction and interference of currents, sand-spits may be straight or curved, or pass from one form to the other (Figs. 457 *a*, *b*). Sand-spits of great extent are shown at the end of the northward projecting forearm of Cape Cod (see Fig. 714), where they have

combined to form the Provincetown headland, now crowned with sand dunes, and in the similar northward projecting strip of land on the New Jersey coast known as Sandy Hook. Smaller sand-spits are built within the waters partly enclosed by both of these larger dune-covered spits. Sand-spits are found on many other parts of our coast, and in our Great Lakes as well (Fig. 457 *a*). They are equally common on foreign coasts.

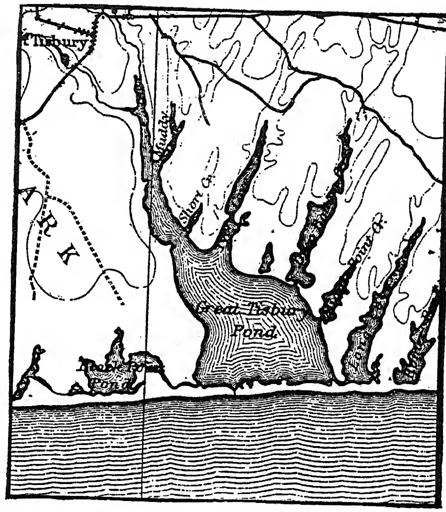


FIG. 457 *c.* — A Bay-bar, with narrow inlet which leaves the water of the bay salty. South Shore of Marthas Vineyard. (U. S. G. S.)

When the sand-spit is built completely across the mouth of a bay, so that only a narrow inlet, or none at all, remains, it is called a *bay-bar*. If the bay remains connected with the sea, its waters will differ little in salinity from that of the ocean; but if the bar is complete (Fig. 457 *d*), the waters of the cut-off lagoon will become fresh if the climate is pluvial, or saltier than the sea if the cut-off is in an arid region. The increase in salinity may also take place if the inlet is so shallow and narrow that there is no free interchange of waters, a condition characteristic of

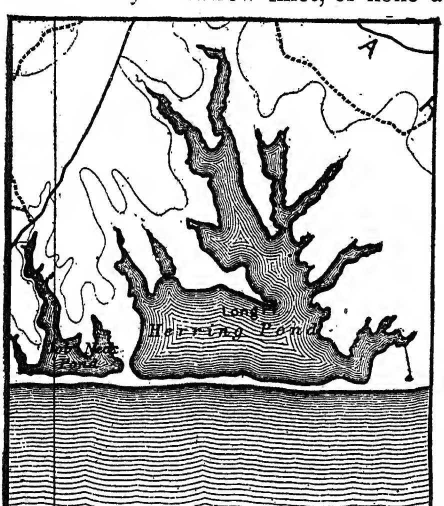


FIG. 457 *d.* — A Bay-bar completely cutting off a bay and converting it into a closed shore-pond. South Shore of Marthas Vineyard. (U. S. G. S.)

tideless waters like the Caspian, where the Kara Bugas Gulf, described on p. 239, forms a typical example. In many such bar-enclosed bays, salt deposits are forming, while in others, situated in pluvial climates, fresh-water vegetation and fresh-water animals replace the marine types which formerly inhabited the bay. In this way may be readily explained the association of fresh-water with marine deposits, which is sometimes found in the older rock series.

FIG. 457 *e.* — Nahant, a rocky headland tied to the shore by a sand beach or *tombolo.* U. S. G. S.

The bay-bar may be formed by a single sand-spit growing in one direction (Fig. 457 *d*) or by two spits growing from opposite sides. The conditions necessary for the formation of such bay-bars are: sufficient supply of detritus or sufficient strength of the long-shore current, or both, to overcome the effects of the currents flowing into and out of the bay, so that the equilibrium is not established until the bay is nearly or entirely closed.

Sand-spits may grow between islands, eventually tying them together, or between an island and the mainland, tying the former to the latter. Such a connecting bar has been called a *tombolo.* It is well illustrated by the bar which unites Great and Little Nahant, and by that which ties this group to the mainland at Lynn, Mass. (Fig. 457 *e*). It is also shown in the beach which unites Marblehead Neck and the mainland (Fig. 716) and in the Nantasket beaches (Figs. 727–730). These examples will be more fully described in a later chapter. A complex shore-form produced by sand-spits is shown in Fig. 458.

Cape Canaveral, on the eastern coast of Florida, illustrates a striking series of modifications produced in the coast line by beach, bar, and spit building by waves and currents (Fig. 459). The

original coastline, shown on the left of the figure, was nearly straight, being the shore of a coastal plain. In front of this was built a *cuspate foreland*, *i.e.*, a triangular projecting land-mass of low relief, with the apex of the triangle pointing seaward. A body of water, known as Indian River, lies between the mainland and the cuspate foreland, which terminates in what is now called the False Cape. An irregular winding stream also bisects this foreland, extending nearly to the apex. This cuspate foreland consists of a series of beaches or bars, built one in front of the

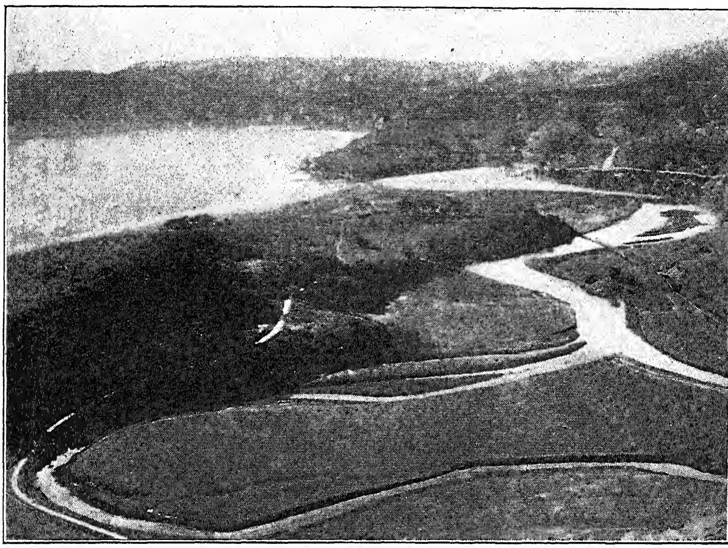


FIG. 458. — Tidal lagoon formed by sand-spit at the mouth of San Luis Obispo Creek, California. Oxbow in the foreground. (G. W. Stose, photo; from U. S. G. S.)

other because of an excessive supply of sand, both from the north and from the south, the relative uniformity in the amount supplied from both directions having determined the symmetry of outline of the old foreland of the False Cape. Such a broad plain, formed of a succession of beach-ridges with shallow depressions or *swales* between, is also called a beach-plain. The swales are sometimes marshy, or may be occupied by narrow lagoons; for the most part they are dry. The ridges are commonly dune-covered.

Such beach-ridges are formed by direct building of new bars in front of the older ones by successive storm waves; by addition

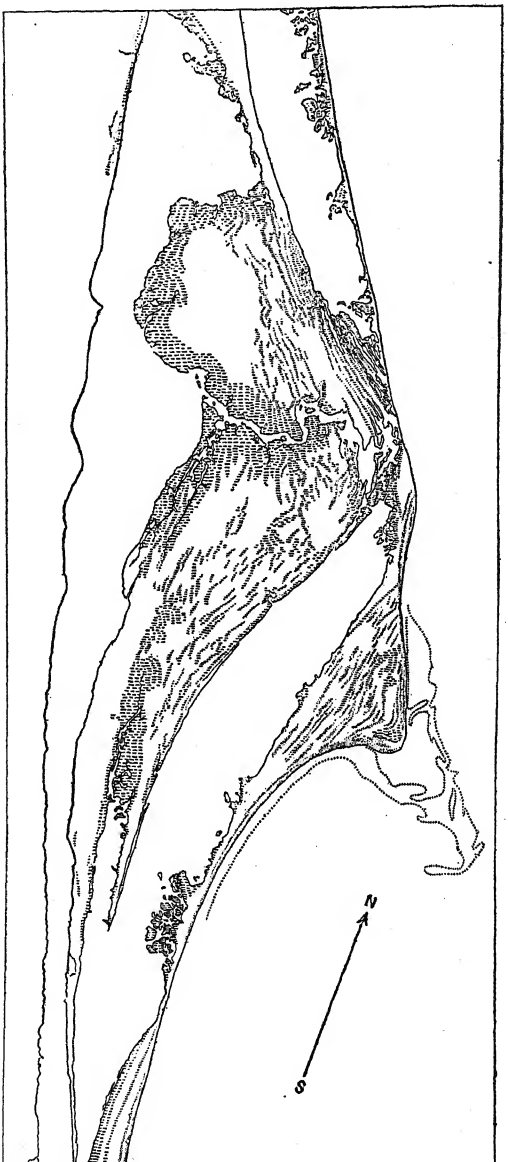


FIG. 459. — Map of Cape Canaveral, Florida. (U. S. Coast Survey chart.) Showing formation of bars, beach plains, spits, etc. For location see map, Fig. 433, p. 512. (Copied from de Martonne.)

of material along the whole front, because of divergence of shore-currents, which then assume a greater cross-section and a diminished velocity, and in consequence permit deposition of transported débris; by the extension of successively formed embankments; or by the interaction of all three processes. Again they may be produced by normal bar-building, one in front of the other, because an excess of débris is supplied by the shore-currents, which become deflected as the result of this building of successive bars.

A pronounced migration of the site of bar-building has produced the later additions, which form the present Cape Canaveral. This

is separated from the older cape by a broad lagoon called the Bananc River, while a similar lagoon lies between the outer bar and the old cape on the north. In front of the present cape is built a new series of sand-spits and bars which are, for the most part, still submerged.

Estuarine Deposits. — Estuaries are indentations in the sea-coast where large rivers enter the sea. They may indeed be regarded as the broadened mouths of rivers, and are often formed by the sinking of the land which is traversed by the lower river valley,

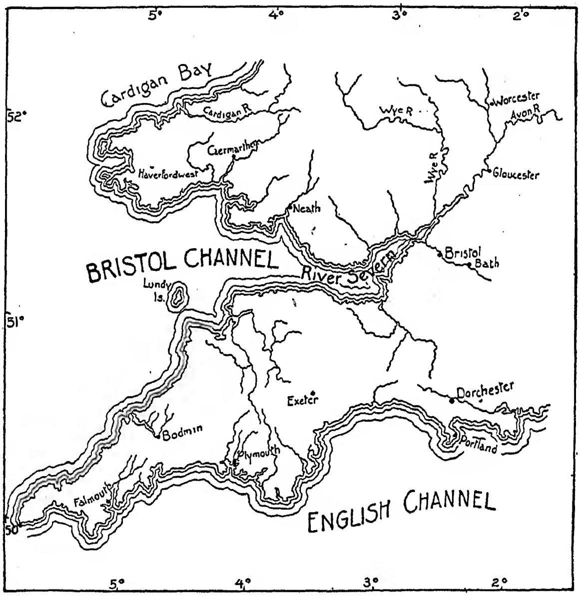


FIG. 460 *a*. — Map of the Estuary of the Severn River, England.

so that the sea has access to this valley. The lower Hudson River is an example of such a submerged valley cut in a rocky land surface, and because of that it has nearly parallel sides. Most estuaries, however, have their sides diverging seawards so that their form is more or less funnel-shaped. The estuaries of the River Severn on the west coast of England (Fig. 460 *a*), and of the La Plata (Figs. 460 *b*, *c*) in South America are of this type. The latter is 125 miles long and receives the waters of the Paraña and the Uruguay rivers, and the currents of these rivers come into periodic conflict with those of the entering tides from the Atlantic. Where the two

currents neutralize each other, sedimentation is most pronounced, the maximum being between 10 and 20 miles above the mouth of the estuary, where slack water conditions may continue for hours. From the sediment dropped here, chiefly the mud brought by the rivers, submerged banks are built up which may eventually rise into islands. At Buenos Aires, constant dredging is necessary, to keep the channels open for navigation. In the narrower channels between the islands, the tidal current, aided by the river currents, will effect scouring and little or no sedimentation

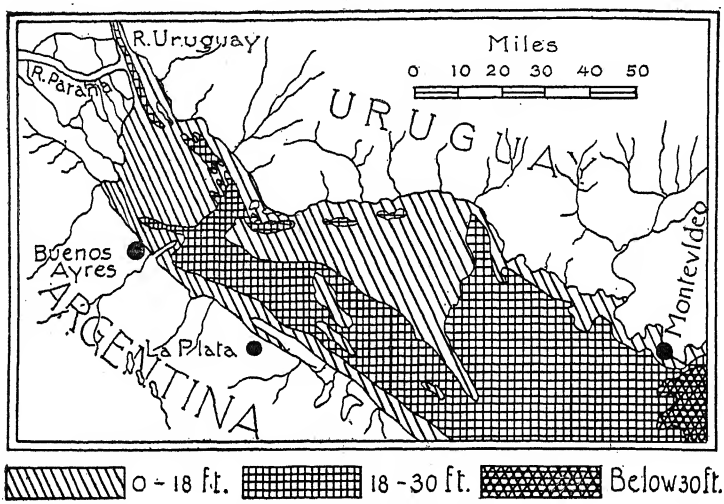


FIG. 460 *b*. — Map of the La Plata Estuary.

takes place. The original length of the La Plata estuary was 325 miles, but about two-thirds of this has been filled up by sediments. In these sediments fine muds prevail, and with them are buried organic remains brought by the rivers.

Marine organisms of floating or swimming habit may also enter with the tide, and being killed by the freshening of the water, their remains become embedded in the sediments. Thus such sediments contain a mixture of marine and fresh-water organisms, though on the whole the organic remains are few in kind as well as number.

The floor of the Hudson, too, has been built up in places by mud deposits to a considerable extent. In these muds have been found

the remains of marine animals of a dwarfed character, this dwarfing being due, according to Shimer, to the freshening of the water.

The waters of the estuary of the Severn, southwestern England, at high tide are thick and opaque with tawny-colored sediments, while at ebbing tide a broad expanse of shining mud-flat is revealed along the coast. Owing to the heavy load of silt in the water, the boundary line between the water and the mud-flat is not easily distinguishable, especially from a distance. Part of the mud is brought down by the river, part of it is derived by wave and current erosion along the banks and is carried into the estuary by the tide. With the muds and fine sands many floating marine organisms, especially Foraminifera,

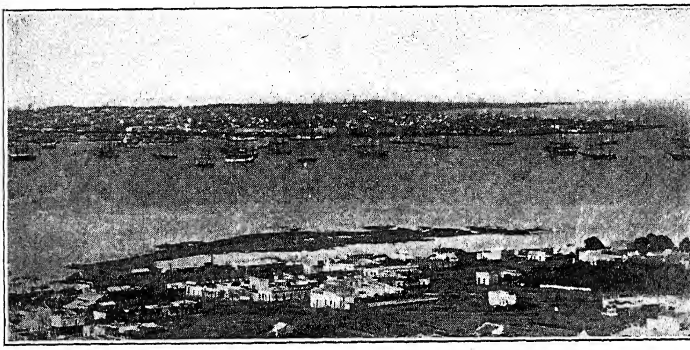


FIG. 460 *c*. — View near the mouth of the Estuary Rio de La Plata (at Montevideo). A mud bank is shown in the foreground.

and the fragments of larger organisms are brought into the estuary and buried in the muds, while farther up the remains of fresh-water sponges and of diatoms are found. Much vegetable matter also occurs in the older muds of the estuary.

A special case of river-borne muds is seen in the Bay of Danzig, on the Baltic Sea, where the river Vistula brings black carbonaceous muds from the Russian plains (the tschernosem, see p. 459). This bay is of low salinity and so corresponds in character to the water of an estuary. Extensive deposits of deep black mud, inclosing dwarfed marine organisms, are formed upon the floor of this bay, and they illustrate one way in which black shales with dwarfed marine organisms may originate.

Deposits in the Off-Shore Shallow Waters

The deposits found between the shore and the edge of the continental shelf, estimated by Murray as covering at present some 10,000,000 square miles, consist mainly of the finer sands, and more rarely of the muds which are washed out from the shores, together with organic and chemical deposits of the type outlined in previous chapters. As we have seen, however, on coasts which fall off

rapidly, and which are bordered by high mountain areas, coarse stream-transported material may be deposited beyond the shore zone.

Since this shallow portion of the sea is the great theater of organic activity, the regions where most of the shell-bearing and other hard-structure secreting organisms live, it is evident that all deposits formed here are likely to inclose the remains of these animals and will therefore be highly *fossiliferous*. Again, large portions of the floor may be covered by sands consisting of the fragments of shells and other calcareous organic structures, as is the case on the floor of large parts of the shallow sea which surrounds the British Isles. In warmer waters coral sands and muds worn from the reefs there building will form an important, if not the whole of the bottom deposit.

In general, deposits formed in these shallower waters are well stratified, but cross-bedding and irregularity of structure are absent. Around coral reefs, however, the slope of the layers is often steep, being sometimes as high as 60 degrees, and interfingering of the clastic and organic deposits produce an irregular structure. (See p. 304.) Ripple marks are common in the shallow parts and may even be developed at considerable depths. These ripples differ in character from those formed on the shore (Fig. 453, p. 537) and in terrestrial deposits (Fig. 371, p. 453), consisting of sharp, symmetrical ridges between regularly concave troughs (Fig. 461 *c*). They represent, indeed, the form of the wave on a small scale, and are due to the oscillatory movement of the water caused by wave motion. Such *oscillation ripples*, as they are called, are readily distinguished from the *current ripples* by their form, but when a relief impression of them is formed, as in the bottom of a layer of sediment deposited over them and perserved by hardening, this relief is not so

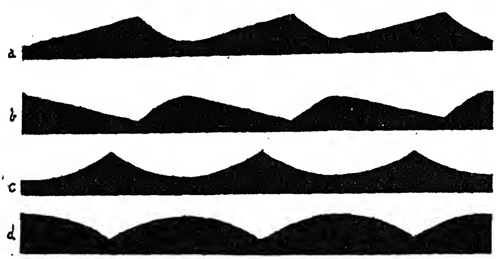


FIG. 461. — Diagram illustrating the forms of ripple-marks and of the reverse impressions of the same. *a*, reverse of current ripple, original position inverted; *b*, form of same; *c*, form of oscillation ripple; *d*, reverse of same, original position inverted. Note contrasting form of two ripples in center (*b*, *c*). Also note general resemblance of *a* and *c*, and *b* and *d*, except for asymmetry of *a* and *b*.

readily distinguished from the normal current ripples, as the difference in angle of slope of the two sides of the latter is not always very great (Fig. 461 *b*, *d*). The significance of this will appear in the discussion of the structure of ancient sediments.

Deposits in the Bathyal Zone

Beyond the edge of the continental shelf we meet the zone of mud deposits, though where conditions are favorable this may extend into shallower water as well. The principal clastic deposits of terrigenous origin in the bathyal zone are blue muds, red muds, green muds, and green-sands. Volcanic sands and muds, either derived from volcanoes on the land or from submarine volcanoes, also cover wide areas, and besides these there are frequently deposits of coral sands and coral muds or clastics of oceanic origin.

The Blue Muds. — These are more often slate-colored, and they are the most widely distributed of the mud deposits, covering an area estimated at 14,500,000 square miles in the several oceans of the world, including the Arctic Ocean. (See map, Fig. 198, p. 277.) In the Gulf of Naples the mud begins at a depth of 15 meters, but its greatest distribution is below the 200-meter (or 100-fathom) line, while the greatest depth from which it has been obtained is 5120 meters. Its upper part is commonly stained red or brown by iron oxide or hydrate, but the lower layers are bluish. In composition it varies greatly; sometimes as much as 97 per cent is clay, while at other times this may fall to 16 per cent. In like manner the content of carbonate of lime varies greatly, ranging from almost nothing to 35 per cent. Quartz in fine grains or as rock flour is a characteristic constituent, and other rock-forming minerals are also present. Some parts of this clay are rich in shells and other hard structures of marine organisms, especially Foraminifera, while in others these are comparatively rare. The fresh mud generally smells strongly of sulphureted hydrogen, due apparently to the decomposition of organic matter. By combination with the iron in the mud, iron sulphide is formed, which may separate out as crystals or specks of the mineral pyrite.

The Red Muds. — Opposite the mouths of tropical rivers such as the Amazon and the Yang-tse-Kiang, the floor of the sea is covered by a red mud which is derived from the lateritic soil of the tropical regions. (See p. 403.) Its red color is due to the high proportion of iron oxide present, a constituent characteristic of the laterite. As in the case of the blue mud, the composition of the red mud varies, pure clay forming from 28 to 68 per cent of its mass, while the content of carbonate of lime ranges from 6 to 60 per cent. Quartz is also a characteristic constituent. The area covered by this mud in the present oceans is about 100,000 square miles. As in the case of the blue mud, the red mud also contains the remains of marine organisms, and with these may readily be mingled organic bodies that were brought from the land by the rivers.

Green Mud and Green-sand. — In the upper slope of the bathyal zone, from the edge of the continental shelf to a depth of 1000 fathoms or over (180–2300 meters), is found a deposit of mud of a character similar to that of the two preceding types, except that it is colored green by the mineral glauconite, which is a hydrous silicate of potassium and iron, often with some aluminum. This mineral forms in the sea under the influence of the decaying organic matter from the elements of the terrigenous muds brought there. Glauconite forms abundantly in the shells of dead Foraminifera, which it fills completely, and on solution of the shell it remains behind as grains of glauconite sand. This constitutes the green-sand; between this and the green muds the difference is mainly one of fineness of grain. The green muds contain from 24 to 48 per cent of clay, and their content of carbonate of lime may be as high as 56 per cent.

Green-sands sometimes constitute extensive formations in the older rock series of the earth, especially those of the Cretaceous period. They are probably not always formed in the same way nor always near the edge of the continental shelf. Some of them contain an abundance of coarse clastic quartz and feldspar grains and have the appearance of having been formed in shallow water.

Volcanic Sands and Muds. — These are especially abundant in the neighborhood of volcanic islands and off those coasts which are characterized by strong volcanic activities. They grade into other types of deposits and may be mingled with calcareous sands and muds to such an extent that on hardening they form impure limestone deposits.

Coral Sands and Muds. — As these are derived by the erosion of coral reefs, their distribution is chiefly in the neighborhood of such structures. They merely represent the finer products of reef erosion carried into the deeper water, where they mostly form beds of lime-mud, which has much the characteristics of the other muds except for the difference in composition. Such muds and fine sands are especially abundant on the floor of the tropical portions of the Pacific Ocean.

Deposits of the Deep Sea

Prevailing Types. — We have already seen that the deeper parts of the sea, the abyssal regions, are chiefly characterized by the accumulation of organic structures (foraminifers, pteropods, coccoliths, diatoms, radiolarians, etc.), derived from organisms which spend their lives in a floating manner in the upper or pelagic district of the sea. With these may be mingled the bones and teeth of aquatic animals (whales, sharks, etc.) and the volcanic dust and pumice fragments which are carried out over such portions of the ocean and eventually reach the bottom. Clastic material is, however, not common in the deep sea, though some of the sands or muds deposited in the bathyal zone may be carried to the deeper waters.

Red Clay. — In some of the deeper parts of the oceans, however, below depths of 2400 to 2600 fathoms, there is a peculiar deep-sea red clay which covers an area aggregating 51,500,000 square miles. (See map, Fig. 198, p. 277.) In color this material ranges from brick-red to chocolate tints, though some samples have a bluish color. When fresh it is soft, plastic, and greasy, but it becomes very hard on drying. It is chiefly derived from the decomposition of volcanic dust which has slowly settled to these depths, along with minute quantities of earthy matter left on solution of the foraminiferan shells, which never reach this depth but are dissolved before they sink so far. Volcanic glass in minute fragments is an abundant constituent, and the silicious structures of the radiolarians constitute an important element of its mass. Manganese nodules and those of other minerals are also present.

This clay accumulates with exceeding slowness upon the floor of the deep sea, so that the teeth of sharks which have lain upon the ocean floor since Tertiary time have in many cases not been so deeply covered by it, but that by dredging they may be obtained alongside of those of species still living in these oceans.

Summary of Structures of Marine Clastics

All marine clastics are well stratified, but cross-bedding structure is found only in the deposits of steep beaches, bars, and spits. There is, however, an inclined stratification in the calcareous deposits around coral reefs (Fig. 228, p. 304). Ripple marks are characteristic of all the shallower deposits. They are commonly of the oscillation type with symmetrical troughs separated by sharp ridges (Fig. 461 *c*). The current type of ripple occurs, however, on beaches and in very shallow water where the influence of currents is manifested (Fig. 453, p. 537). On the beaches we also find the cusps, which are sharp ridges projecting at right angles to the shore and separated by concavities (Fig. 451, p. 535).

Rill marks formed by the running off of waters are common upon beaches and tidal flats, but their character is generally the reverse of those formed on inland mud surfaces. On the coast, rill marks are formed by the union of many minor rills into larger ones, being thus more of the nature of miniature river systems, while the rill marks on inland flats are comparable to the distributaries of rivers on the delta. This type, however, also occurs upon the beach (Fig. 462). Other structures restricted to the beaches are wave marks, sand-ridges behind shells and pebbles, and shallow gougings of the sands and muds around various objects. Certain markings due to shore ice and ice crystal growth, and channels due to dragging of seaweeds and other objects over the floor of shallow water may also be mentioned. Mud-cracks, raindrop and

footprint impressions, on the other hand, so characteristic of river flood-plains and playa surfaces, are rarely preserved in sea-coast deposits, though this may be the case in special regions where muddy surfaces are exposed for long intervals between highest tides.

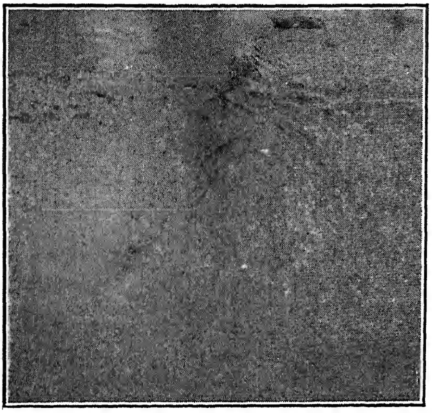


FIG. 462. — Rill marks upon the coast of Rockaway Beach. (M. O'Connell photo.)

Above all, however, marine clastics are characterized by the presence of organic remains (shells, etc.) which are seldom absent over wide areas or through successive layers. Indeed, such organic remains may be regarded as the surest indication of the marine origin of older sediments and very often the only reliable one. If the remains of marine organisms are absent from a formation of wide extent and great thickness, it may reasonably be concluded that that formation was not deposited under normal marine conditions.

Lateral Changes in Facies and Overlap Relations of Marine Clastics

Change in Facies

When we consider the deposits formed in the sea at a given time, it is evident that they cannot be of uniform lithological character throughout. Close to the shore, pebbles may accumulate, while at the same time sands are deposited farther out to sea, and at a still greater distance muds are forming. At another place the shore deposit may be wholly quartz sand, but as we pass seaward, especially in tropical regions, the sands may become more calcareous, for the material worn from a coral reef at some distance from shore may become mingled with the shore-derived terrigenous quartz sands. Finally, at greater distances from shore, the quartz grains may disappear and lime-sands and lime-muds will alone be deposited. Thus when we consider the deposits formed in a given

short period of time as a whole, we find a lateral gradation in facies from the shore outward. Either the change is from coarse terrigenous deposits at the shore to fine ones at a distance from shore,

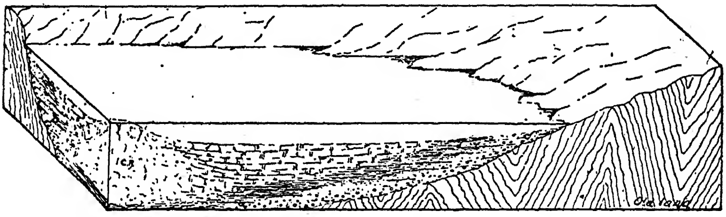


FIG. 463 *a*. — Diagram illustrating change in facies of marine clastics, from sands and muds near the shore to calcareous beds near coral reefs, etc. Note also the overlap of the successive formations. (From *Principles of Stratigraphy.*)

or it is from terrigenous sands to ocean-derived (coral) sand and muds (Fig. 463 *a*). Such a lateral gradation in character of material or in *facies* is practically universal for marine deposits.

Overlaps and Off-Laps

Progressive Overlap. — When the sea slowly advances upon a sinking land, it is obvious that from period to period of deposition there is a shifting of the facies in the direction of transgression. In the case of varying terrigenous deposits, the pebble zone of the second stage of deposition comes to rest farther up on land than

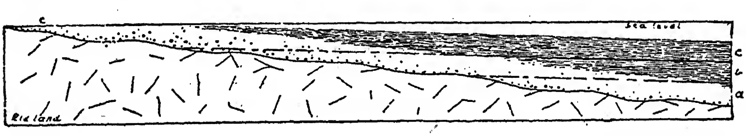


FIG. 463 *b*. — Section to show normal progressive overlap of the formations *a–c* and their shoreward change from muds to sands and pebbles. (From *Principles of Stratigraphy.*)

that of the first, while the sand zone of the second stage is shifted so as to rest more or less upon the pebble zone of the first, and the mud zone of the second in part upon the sand zone of the first. With further advance of the sea, a continued shifting of the zones in the same direction takes place, until the mud zone of the last stage may rest vertically above the pebble zone of the first, being separated from it, however, by a sandy zone (Fig. 463 *b*). Similar

conditions occur when the lateral change in facies is from quartz sand to coral sands or muds (Fig. 463 *c*).

It is further evident that if we separate the deposit formed simultaneously at the different periods or stages of deposition we shall find not only a lateral change in facies in each, and essentially the same type of lateral change, but we shall also find that the deposits of each successive period or stage extend farther up on the old land than did those of the preceding period or stage. In other words, the deposits of successive stages progressively overlap one another in the direction of sea advance. This is illustrated in the diagrams (Figs. 463 *b*, *c*), in which the periods of deposition are lettered from below upward, or in the order of formation.

It must be recognized, however, that such overlaps are of significance only when they extend over wide areas and long time intervals, for though now and then such structures can actually be seen

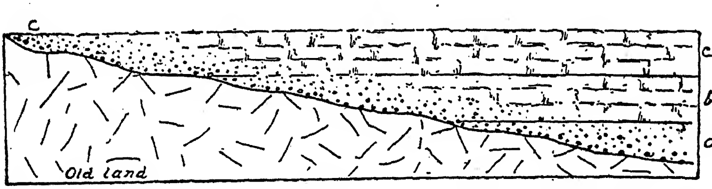


FIG. 463 *c*. — Section to show normal progressive overlap of marine formations *a*–*c*, and their shoreward change from limestones to sandstones.

in small sections, it usually requires the comparison of sections at a distance from one another to bring out this relationship. Moreover, it is necessary to have some means by which the different divisions of the series can be separated from one another, and by which the same division can be traced from point to point. In a series, the formation of which occupied a considerable period of time, the organic remains or fossils serve such a purpose of identification, for the character of the organisms undergoes a progressive change from period to period, and at each period the organisms peculiar to it are distributed over much if not the whole of the area in which the sediments of such an overlapping series are formed. Thus, in the following illustration (Fig. 464), we may assume that each one of the divisions from *a* to *c* had its own peculiar organic remains which form its "index fossils," and that the index fossils of each are distributed horizontally over the entire extent of the division.

If we now examine the deposits of such an overlapping series,

which we will assume have been consolidated into rock and have been subjected to considerable erosion, we may find the following conditions along a line at three points, each separated from the other, we will assume, by an interval of fifty miles. The only exposure at locality *A* is a cliff of sandstone resting with a basal pebble bed upon the crystalline rocks (granite or gneiss). At *B*, fifty miles distant, we find a river valley cut into horizontal beds down to the underlying crystalline rocks. Here we find again a sandstone and basal pebble bed resting upon the crystallines, and we might assume that this was the same sandstone which we found resting upon the crystallines in section *A*. This assumption would, however, be erroneous, as we shall see. Overlying this lowest series are sandy muds and finally beds of clay rock. Fifty miles farther in

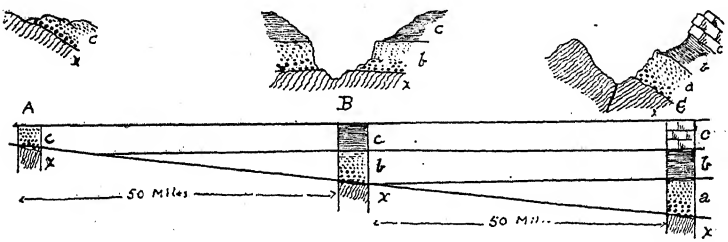


FIG. 464. — Natural and columnar sections at each end and at the center of a line 100 miles long and at right angles to the original trend of the shore. The progressive overlap and change in facies is shown. Note that in each section the clastic formation next above the crystallines is a sandstone, but that it belongs to different formations in each.

the same direction we meet with the outcrops at *C*, where the beds have been disturbed (by faulting and tilting; see Chapter XIX), and here we find a still more extensive series of stratified beds resting upon the crystallines, but beginning again with a sand and pebble rock followed by a succession of beds very similar to those seen at *B*, but with an additional formation at the top which contains more or less lime.

If we now study the index fossils of the successive divisions *a* to *c* at *C* and then compare them with the index fossils found in the two divisions shown in the river gorge at *B*, we shall recognize that the two divisions at *B* correspond only to the upper two (*b* and *c*) at *C*, although in their physical characters, that is, their petrology, they resemble the lower two. In other words, the lowest division at *B* has the same fossils as the second division at *C*, although

in its general character it resembles the first division at *C*. In like manner the second division at *B* corresponds to the third division at *C* in its index fossils, though in its physical characters it corresponds more closely to the second division at *C*. Now extensive studies have shown that index fossils are more reliable guides than are the physical (lithologic) characters of the formations, and from this we conclude that the formations exposed at *B* represent divisions *b* and *c* as shown at *C*, formation *a* being absent at *B* through overlap, while the physical characters or facies of *b* and *c* have changed laterally. From the character of the index fossils we further conclude that the only bed shown at locality *A* corresponds to bed *c* at *C* and *B*, though in its physical characters it resembles bed *b* at *B* and bed *a* at *C*. Beds *a* and *b* are thus entirely absent at *A*, having been overlapped by bed *c*. In the chapters on historical geology, in the later part of this book, we shall give several examples of such overlaps.

Progressive Offlapping. — In the foregoing section we have dealt with the arrangement of strata produced in a transgressing

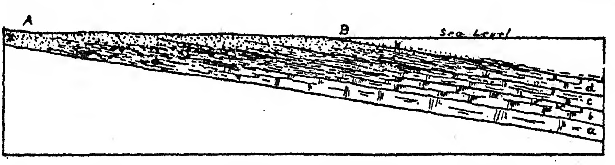


FIG. 465. — Section to illustrate the arrangement and change in facies in an offlapping series formed during a retreatal movement of the sea. Note that at *A*, only the lowest bed (*a*) is present as a sand-facies, this being limestone farther out at sea. At *B* all the formations are present, the highest (*d*) being sandy, the lowest calcareous. (From *Principles of Stratigraphy*.)

sea. The reverse condition obtains in a retreating sea, forming a regressive series. Here each succeeding division will cover a lesser area than the preceding one, and a portion of the older one is always exposed beyond the younger. This is illustrated in the preceding diagram (Fig. 465) in which the sea is assumed to have successively retreated from *A* to *B*. As the shore line retreats, the types of deposits will change with it, and the zone of sands will migrate seaward with the retreat, and come to rest upon the finer muds, etc., which were previously deposited here while the shore stood at *A*.

If now we have natural exposures of such a series (Fig. 466) we shall find that the sandstone bed at *A* has the fossils of division *a*,

while the beds at *B* are known by their fossils to be, respectively, beds *a* and *b* instead of *b* and *c*, as in the transgressive series (Fig. 464). At *C* all three beds are exposed. Moreover, it will be seen that in general the change in the physical characters of the successive beds is the reverse of that seen in the previous series, the

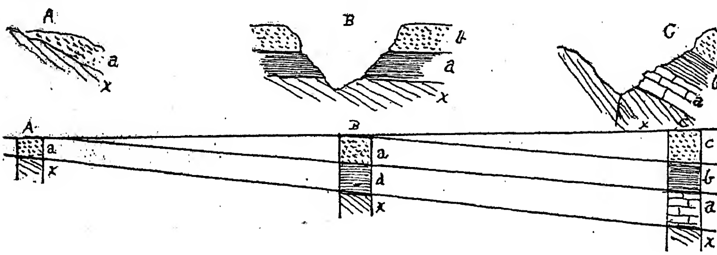


FIG. 466. — Natural and columnar sections at each end and in the center of a line 100 miles long and extending at right-angles to the original shore-line.

finer ones (muds and calcareous beds) being at the bottom and the sands at the top. The top sandstone is one of *emergence*, whereas in the previous series of sections the bottom sandstone was one of *submergence*. Conditions of this kind, though rarely as simple as here outlined, are found in nature and some of them will be discussed in later chapters.

Compound Regressive and Transgressive Series

Offlaps Followed by Overlap. — It is obvious that if, after a retreatal movement of the sea and the formation of an offlapping series as outlined in the preceeding section, a transgressive move-

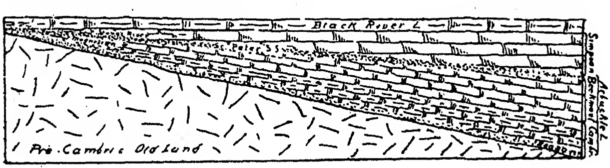


FIG. 467. — Section to illustrate the relationships of strata formed by a compound, transgressing, retreatal and transgressive movement of the sea with the resulting overlapping, offlapping and overlapping series separated by a compound sandstone of emergence and submergence. (From *Principles of Stratigraphy*.)

ment with overlapping of formations should follow, the sandstone bed of emergence would be in part reworked by the advancing waters and transformed into a sandstone of submergence, at least

in its upper part. Thus a complex series would be produced, separated by this compound sandstone. The resulting relationships of the strata are shown in the diagram (Fig. 467, p. 559), which represents an actual case of a transgressive, followed by a regressive, and again by a transgressive series. The appearance in the exposures of such a series is shown in the next figure (Fig. 468).

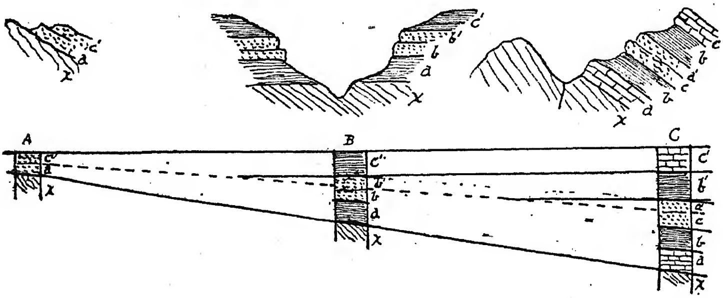


Fig. 468. — Natural and columnar sections to illustrate compound off-lapping and overlapping series.

At locality *A* the sandstone of emergence, *a*, is followed by the sandstone of submergence, *c'*. At locality *B* these two sandstones are represented by formations *b* and *b'*, respectively, and at locality *C* by *c* and *a'*. In both localities *B* and *C*, this compound sandstone will occupy the middle of the series and the other beds will become finer grained both downward and upward.

Replacing Overlap. — When a series of delta or other clastic beds is built outward from the land, while a series of marine beds

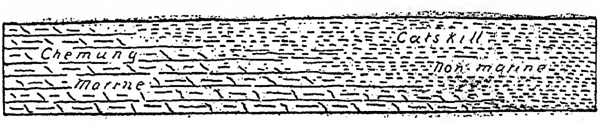


Fig. 469 *a*. — Diagrammatic section to illustrate replacing overlap of shore or continental sands on the right and marine shales, sandstones and calcareous beds on the left. (From *Principles of Stratigraphy*.)

such as limestones is forming farther out to sea, the advancing deposits from the land will progressively overlap the purer marine deposits, successively replacing them. This relationship is shown in the preceding diagram (Fig. 469 *a*). Instead of delta or other clastic seashore deposits (of terrigenous origin), deposits of purely continental character may progressively replace those of marine

character, the resulting relationships being essentially similar (Fig. 469 *b*). The replacement may be abrupt or gradual, or on account of oscillations the two series may interfinger in various degrees along the line of contact.

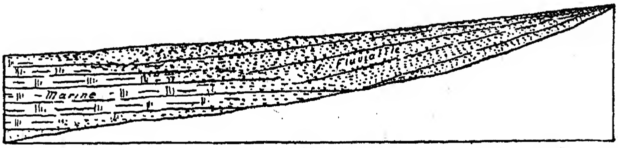


FIG. 469 *b*. — Diagrammatic section to illustrate the overlap of continental beds over a retreatal marine series. (From *Principles of Stratigraphy*.)

In the following two diagrams such replacing series of various types are shown (Figs. 469 *c*, 469 *d*). These represent interpretations of actual cases, as are also the simpler ones shown in the

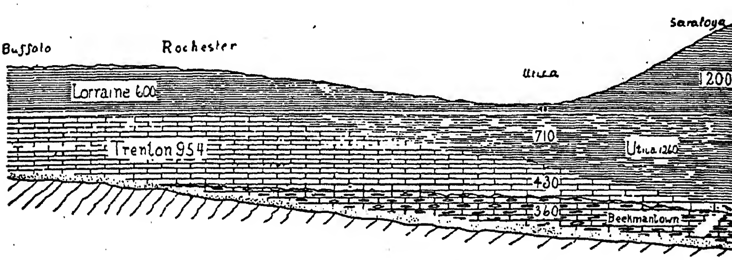


FIG. 469 *c*. — East-west section across the state of New York, showing the various types of overlap characteristic of the formations. The depression at Utica is due to subsequent erosion. The strata were formerly continuous. (From *Principles of Stratigraphy*.)

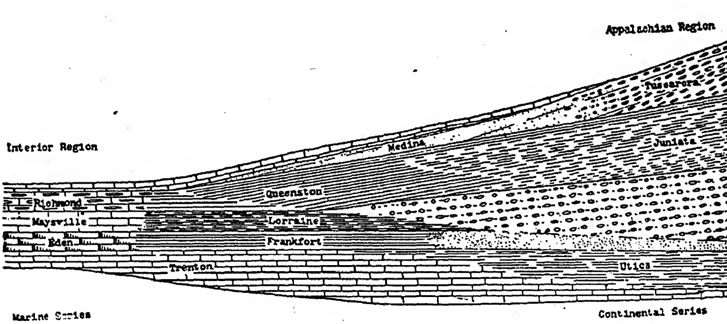


FIG. 469 *d*. — Restored section from the Appalachians to the Cincinnati region, to show the overlaps of continental and marine strata. (From *Principles of Stratigraphy*.)

preceding figures. In the next figure (Fig. 470) non-marine, *a*, and marine, *b*, overlaps are compared, the former overlapping

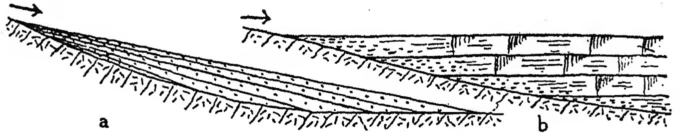


FIG. 470. — Sections to illustrate progressive overlap; *a*, in a continental series, away from the source of supply; *b*, in a marine series towards the source of supply. (From *Principles of Stratigraphy.*)

primarily away from the source of supply of terrigenous material, the latter towards it, the source being indicated by the arrows.

CHAPTER XVIII

CONSOLIDATION OF CLASTIC MATERIAL; TYPES OF CLASTIC ROCKS

Consolidation of Clastics

With the passage of time clastic material is in most cases bound together into solid rock, but the degree of such solidification does not always correspond to the length of time during which these deposits have existed. Thus in the Baltic provinces of Russia there are sands and muds which belong to the oldest deposits of the Palæozoic era, deposits which everywhere else have been completely consolidated into rock, or, as it is technically expressed, have become thoroughly indurated. The Russian deposits, on the other hand, are for the most part still unconsolidated, though in some cases this may be the result of later removal of the binding substance which once had indurated them. On the Atlantic coast of New Jersey and Maryland are soft clays and sands of the same age as the consolidated chalk beds of England and France and of the hard limestones and other rocks of the Alps. Finally, some comparatively young deposits, formed during the ice age, are already solidified in certain regions, the most noted example being the great pebble beds called "Nagelfluh" which form some of the remarkable hills in the city of Salzburg, Austria (Fig. 471 *a*). These are honey-

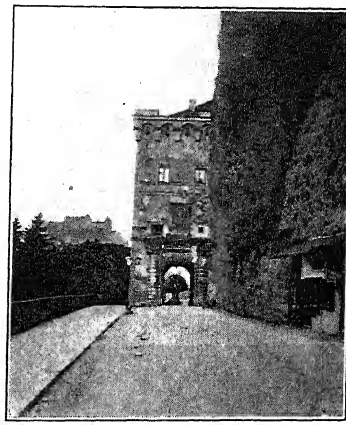


Fig. 471 *a*. — Roadway, cut along the side of a cliff of consolidated glacial gravels (Mönchsberg). The rock, which is called Nagelfluh, because of the resemblance of the depressions left by the pebbles when removed, to that formed by a large nail-head, forms partly overhanging cliffs and is in places tunneled by roadways. Salzburg, Austria.

combed in places by catacombs which date back to Roman times (Fig. 471 *b*). Deposits of lime-sands and muds are frequently

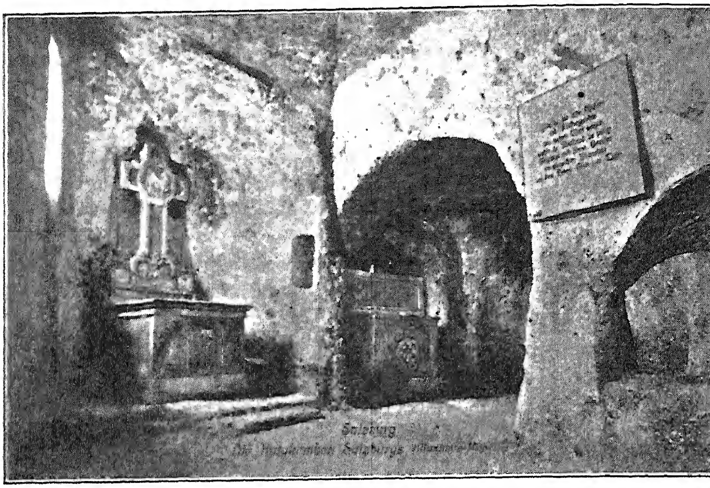


FIG. 471 *b*. — Maximus Chapel, in the Catacombs of Salzburg (Roman Juvavum). These catacombs are hewn out of the Nagelfluh, or consolidated glacial gravels. They date back to the third century.

bound together very shortly after their formation, especially in the sea, where cementing lime is deposited by precipitation from solution in the sea-water.

Causes and Agents of Induration

Clastic material may become consolidated or indurated in a variety of ways, the chief of which are through pressure, by infiltration of a cementing medium into the pores, or by recrystallization and the formation of new minerals which bind the grains together. The last method belongs to the changes due to metamorphism, and will be more fully discussed in Chapter XX. The others may be briefly considered here.

Induration by Pressure. — When an older is buried beneath younger sediments, the pressure of the latter will tend to bring the grains of the older more closely together, forcing out the air and water from the pores. This will result in a certain amount of interlocking of the grains and cause them to adhere to one another more or less firmly. When sand grains are thus pressed together a soft

sandstone is produced, which because of its ready yielding to the stone-cutter's tools is called a *freestone*. Finer-grained clastic deposits are more strongly solidified in this manner than those of coarser grain, and thus strata of clay and rock-flour may be changed into a rock called *shale* (Fig. 473, p. 570). There is probably in all cases a certain amount of cementation by mineral matter, and in the older deposits there is generally some recrystallization as well.

Induration by Cementation. — The common cements which bind clastic fragments together are carbonate of lime, silica, and iron oxide. Carbonate of lime is of course the chief cementing agent of all calcareous deposits, but it also binds quartz grains and pebbles into a calcareous sand or conglomerate, and it may be an important cementing agent of muds of various kinds. When sand and pebble beds are penetrated by waters which carry lime in solution, either rising from below or descending through a soil rich in lime or through an overlying calcareous deposit, the grains and pebbles are quickly cemented into a solid rock, just as sand grains, pebbles, and large blocks are cemented into an artificial rock mass by mortar, which is mainly carbonate of lime. Silica brought in solution by water will cement many kinds of fragmental material, but is especially effective when the clastic material consists of pure quartz grains. In such cases, the silica will be deposited around the grains in such a way that the physical (especially crystallographic) characters of the new quartz will be continuous with the quartz grain of the clastic sands. This is called secondary enlargement of the clastic particles and is of common occurrence (Fig. 472). When the process has gone so far that the grains are no longer distinguishable a bed of *quartzite* is produced.

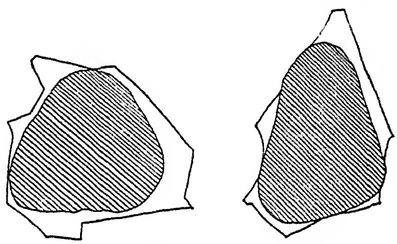


FIG. 472. — Well-rounded quartz grains from ancient eolian rock (shaded), enlarged by secondary addition of silica in optical continuity with the old quartz. Sandstone Dike, Buffalo, N. Y. (Much enlarged.)

Iron oxide is a common cementing agent especially of impure sands. Such sands are then colored yellow or brown, forming the familiar brownstone so much used in the past for dignified buildings.

Classification of Clastic Rocks

Important Characters. — When we remember that the clastic material from which the clastic rocks are produced is the product of rock destruction or fragmentation, it is apparent that in any natural classification the agent causing this fragmentation demands first consideration, just as the medium from which the various chemical (endogenetic) rocks were separated out, and the agent active in the separation, demanded our first attention among the non-clastic rocks. In those non-clastics, the formation of the rock from the magma or the state of solution and vapor, was primarily a chemical process, and therefore the chemical composition of the medium and of the resulting rock was of next importance. In the case of the clastic rocks, however, the chemical composition of the material from which the clastic matter is derived (that is, the older rocks) is of less significance, since it plays generally only a subordinate part in the process of clastation. Of much greater significance as indicative of the kind and amount of destructive work performed, is the coarseness of the fragments produced, and it is this degree of coarseness which in the consolidated rock produces its grain or *texture*. Hence, in the clastic rocks, texture may be considered of more importance than chemical composition, whereas in the non-clastics the reverse was true. Chemical composition, it is true, may play a very important part in clastic rocks as well, as for example in limestones and in clay rocks, but this composition is never constant over more than very small areas, because clastic rocks, more than any other, are subject to the mechanical mixture of materials of varying composition. We shall then, in the classification of clastic rocks, consider the basis of subdivision in the following order: (1) agents of clastation, transportation, and deposition; (2) size of grain or texture; (3) chemical composition; (4) other characters.

Classification according to Agents of Clastation, Transportation, and Deposition

It is obvious that these activities may not always be due to the same agent, though there are examples where this is undoubtedly the case. Thus sand and larger-grained fragments worn by the waves of the sea from a cliff of older rock, transported by waves and currents, and deposited in quieter water in the ocean, are throughout

the product of sea erosion, transportation, and deposition. Fragments broken from rocks by a river current, transported by it, and deposited upon the flood-plain or alluvial fan, form, throughout, a river-made deposit. So too, a rock is, throughout, a wind-formed or eolian rock if the fragments are removed from the older rock by the erosive action of the wind, and if they are transported and deposited by it. While such pure types, as they may be called, are perhaps not at all uncommon, actual purity of origin will be very difficult to determine in any but the simplest cases. Thus the sands transported by and deposited in the sea may have been furnished to it by rivers, — a very common occurrence. The sands washed away by the rivers or blown away by the wind may originally have been the product of disintegration and decomposition under the atmosphere or they may be the product of glacial erosion. Indeed, it is probably true that clastic deposits and the clastic rocks formed from them have, as a rule, a varied history and are the product of the interaction of various agencies. Only in the consolidated residual soils, — the product of atmospheric decay or weathering without transport, — can we be reasonably sure that but one agent, the atmosphere, was active in their production. To state it in another way, most clastic rocks are of multiple parentage — they are *polygenetic* — though some are of single parentage, or *monogenetic.*

If it is not possible to determine all the agents active in the production of a given rock, we are constrained to give prominence to the agent which has impressed its most characteristic features upon the deposit, and this is commonly the last of the agents, namely, that effecting deposition, or the medium by and in which the material was deposited. Thus an eolian rock is one deposited by wind upon dry land, whatever the origin of the material. If the origin can be determined, this adds to the precision of the classification. Thus certain eolian beds may consist wholly of volcanic fragments, *i.e.* pyroclastic material. Others again, like the loess, are believed to be in part of glacial origin.

In general, it may be said that the origin of rocks according to agent is a matter primarily for field determination, and one only rarely indicated in small fragments. True, a marine rock may always be recognized from its fossils, and so may a lake or pond-formed rock. But when fossils are absent, as they may be even in rocks thus formed, there is no positive indication of origin. In-

deed, some rocks may be wholly composed of minute shells of marine organisms and yet be wind-laid deposits, as in the case of the Miliolitic limestone of India, already referred to (p. 278). Again, a rock may show all the purity, roundness of grains, and uniformity of their size, characteristic of wind deposits, and yet may be reworked by marine waters and so be a typical marine rock.

Taking first, then, the agent or medium which has given the clastic rock its most distinctive character, we may distinguish the following types:

1. **Residual Rocks.** — Those formed in place by disintegration and decomposition with little or no transport (*Atmoclastics*).

2. **Eolian Rocks.** — Those transported and deposited by wind upon dry land (*Anemoclastics*).

3. **Water-laid Clastic Rocks.** — Those deposited by and in water (*Hydroclastics*). Among these we may distinguish:

(*a*) *Marine Clastics.* — Those deposited in the open sea.

(*b*) *Estuarine Clastics.* — Those deposited in estuaries.

(*c*) *Lacustrine Clastics.* — Those deposited in lakes, ponds, and playas.

(*d*) *Fluviatile Clastics.* — Those deposited on river flood-plains, alluvial fans, and deltas.

4. **Volcanic Clastics.** — Those produced by volcanic explosions, and primarily settling down without much reworking by wind or water (*Pyroclastics*).

5. **Fault-Crush and Glacial Clastics.** — Those produced by the movement of one rock mass past or over another, including those produced by ice erosion (*Autoclastics*).

6. **Organically Produced Clastics.** — Those produced by the rock-breaking activities of organisms, a small class except for artificial rock-masses produced by man (*Bioclastics*).

The Texture of Clastic Rocks

The texture of clastic rocks is their most obvious character and the one most readily determined in hand specimens or other fragments which may give no indication concerning the agent active in their formation. Hence clastic rocks are more often classified by their textures than by any other character.

Three main types of texture may be recognized, the coarse, intermediate, and fine, according as the material consists primarily of

coarse fragments (rubbly material), of sand grains, or of impalpable rock-flour or clay. Three terms will here be used to express these textures.

1. **Rudaceous**, for the coarse rubbly texture (Latin, *rudus*, rubble).

2. **Arenaceous**, for the sandy texture (Latin, *arena*, sand).

3. **Lutaceous**, for the rock-flour and clay-size texture (Latin *lutum*, mud).

Accordingly three textural types of rock may be recognized: (1) the rubble-rock or rubble-stone, or **rudyte**, which when the fragments are rounded is a *conglomerate* and when angular a *breccia;* (2) the sand-rock or sandstone or **arenyte**; and (3) the mud-rock or mud-stone, or **lutyte**.

Several distinct types can be recognized under each division, but as these are further modified by the composition, this will be considered first.

Composition of Clastic Rocks

All clastic rocks which have been subject to prolonged transport and sorting of material before consolidation will be relatively pure, or of more or less uniform composition. With material derived from crystalline rocks (igneous or metamorphic) quartz will predominate, and in exceptional cases the rock may consist wholly of quartz, as in that of the Sylvania sandstone of Ohio and Michigan already referred to (p. 440), and of the Shawangunk and Olean conglomerates of New York state. In other cases the rock may contain large quantities of feldspar because there has been little transport and sorting. Such are the arkose sandstones of New Jersey (Triassic) and the arkose Torridon breccia or fragment rock of Loch Marie and other regions of West Scotland (pre-Cambrian), which looks superficially like a coarse granite, having been produced by the disintegration of such rock and the recementation of the material.

When the materials of a clastic rock are derived from the erosion of a coral reef, or shell accumulations, or older limestones, the grains and larger fragments are apt to be pure calcium carbonate with little or no admixture of other material. This produces a lime sandstone (*calcarenyte*) — such as that found on Bermuda, or a limestone breccia (*calcirudyte*), of which the Point of Rocks "Marble" of Maryland is an example.

The mineral glauconite is often a characteristic constituent of sands, as we have seen (p. 552), and thus *glauconitic sandstones* may be produced. When iron oxide abounds as a cementing agent, *ferruginous clastic* rocks (sandstones, conglomerates) are produced. When the material of the rock is largely clay, its texture is that of a mud-rock, or *lutaceous*, and the rock becomes a *claystone* or *argillite* (Latin, *argillum*, clay). When clay is one, but not the only constituent, the rock is called *argillaceous*. Rocks of all textures may be

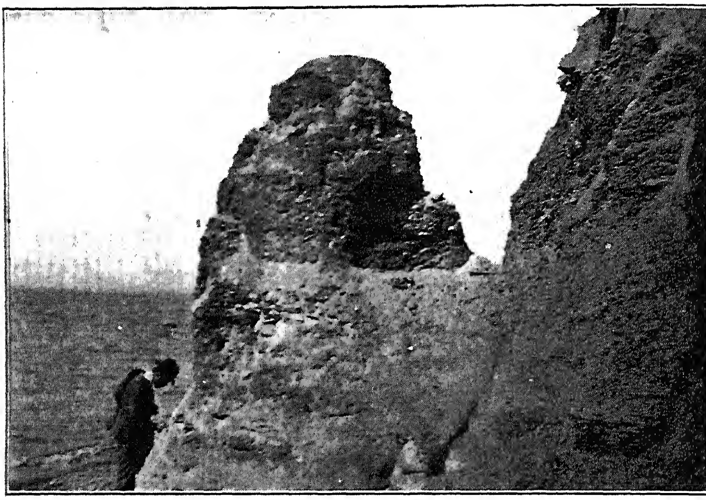


FIG. 473. — A bank of typical shale (Hamilton formation, Devonian) on the shore of Lake Erie. The shale splits into small chips on exposure, and rapidly weathers to clay. It is full of marine fossils. (Photo by the author.)

argillaceous, those of rubbly (rudaceous) texture and those of arenaceous texture generally carrying the clay as an admixture or as part of the cement. When carbon is present, the rock is called *carbonaceous*.

While there are other composition types, the silicious, calcareous, and argillaceous are the most common, and from a purely chemical point of view these are called quartz-stones, limestones, and claystones. Other substances are present chiefly in smaller quantities and form modifications of these primary types. It must, however, be remembered that there are quartz rocks and limestones of other than clastic origin.

Structural and Other Characters Used in Defining Clastic Rock Types

Shaly and Slaty Structures. — Certain structures are so commonly associated with special composition and textural types of clastic rocks, that they have been made the chief basis of classification. Mud-rocks (lutytes) in which much clay occurs (argillaceous) generally show a peculiar mode of breaking in small plates parallel to the bedding, these plates having curved surfaces (gently convex on one side and concave on the other) which give the fragment a superficial resemblance to a piece of a shell. On this account the name *shale* has been given to such rocks and the structure is spoken of as *shaly* (shelly). When exposed, typical shales quickly split into thin chips, and weather into clay (Fig. 473). The term shale is, however, loosely used for all kinds of mud-rocks which split into thin layers, whether these are shaly, *i.e.* have curved surfaces, or are smooth-surfaced. To the latter type the term *fissile shale* is sometimes applied, and the name slate is also popularly used in some cases where this smooth splitting is parallel to the bedding surfaces (Genesee Shale, Fig. 474). Such rock is generally well jointed or separated by vertical planes with smooth faces. True slate, however, is a metamorphic mud-rock, the splitting into thin plates having, as a rule, no reference to the original bedding, but being secondarily produced. (See Fig. 562.)

Fig. 474. — A bank of fissile shale (Genesee Shale, Upper Devonian) exposed in the gorge of Eighteen Mile Creek in western New York. Note the perfect jointing. The rock splits into thin slate-like sheets parallel to the bedding. (Photo by the author.)

Platey Structure. — When rocks split into layers a few millimeters or centimeters in thickness, and with smooth surfaces which

are generally the bedding planes, they are called *platey rocks*. The most common platey rocks are calcareous and fine-textured or lime-mud-rocks (calcilutytes). Such are the famous platey layers of the Solnhofen region in Bavaria (Plattenkalke) (Fig. 475), which are used for roofing purposes in that country. Many other limestones in our own and other countries split into thin layers, producing suitable materials for "tablets of stone" on which inscriptions can easily be engraved on account of their softness. When seen in sections, such thin-bedded limestones often present a banded aspect, and they are then called ribbon limestones (Fig. 476). They abound among the older formations.

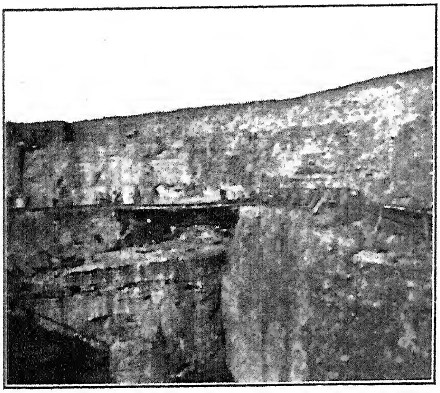


FIG. 475. — Deep quarry in the lithographic and platey limestone deposits (Jurassic) of Solnhofen in Bavaria. Most of the rock consists of thin layers (platey strata), but between these are the thicker, purer layers which furnish the lithographic stone. (Photo by author.)

Concretionary Structure and Concretions. — The name *concretion* is applied to a stony mass included in stratified rocks and which has been formed as the result of segregation of material either during the deposition of the rock or afterwards under the influence of circulating waters or otherwise. Concretions are very common in clay rocks or unconsolidated clay beds, and generally consist of clay bound together by carbonate of lime or carbonate of iron. In form they vary greatly from spherical to disk-shaped (Fig. 477 *a*), often compound (Figs. 477 *b* and *c*), cylindrical, tubular, or irregular (*Loesspüppchen*), etc., fre-

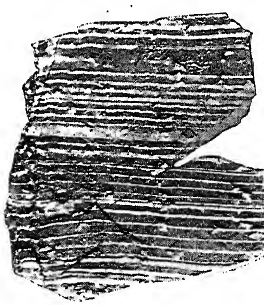


FIG. 476. — A piece of "ribbon limestone" or thin-bedded, fine-grained lime-mud-rock (calcilutyte) seen in section at right angles to the bedding. Cambro-Ordovician beds of Pennsylvania, slightly reduced. (Photo by Bela Hubbard.)

quently simulating organic forms (Fig. 477 *d*). Sometimes the entire rock may be a mass of such concretions, as are certain beds of the Magnesian Limestone on the coast of Durham, England, already

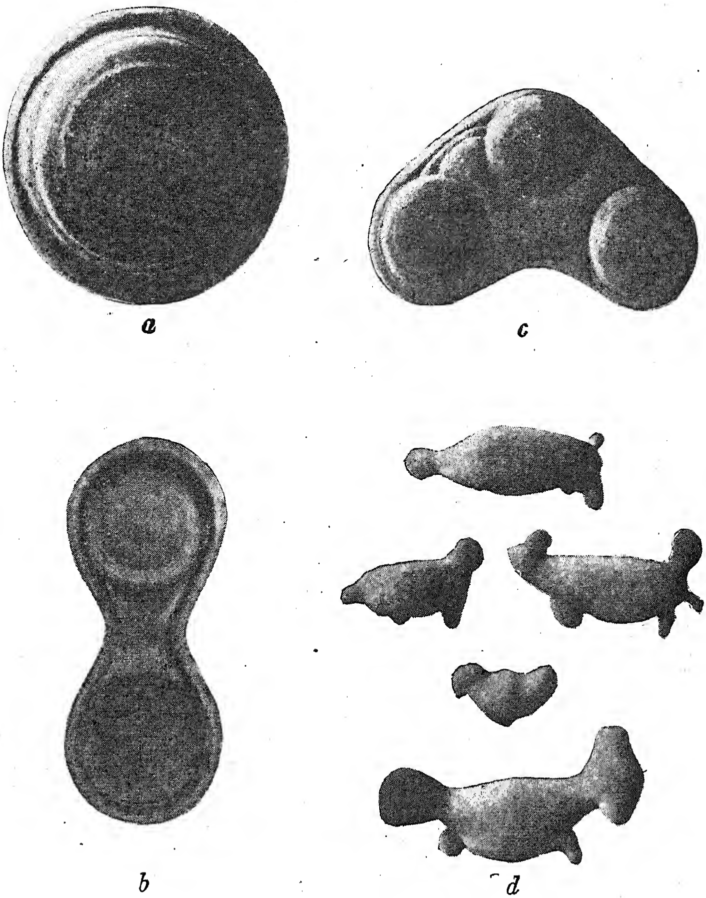


FIG. 477. — Clay-stone concretions from the glacial clays of the Connecticut valley. (After J. M. Arms Sheldon.) *a*, single disk-shaped form, about three fifths natural size; *b*, confluence of two disk-shaped forms, one half natural size; *c*, three confluent disks, about one half natural size; *d*, forms imitative of animal shapes (Loesspüppchen) less than half natural size.

referred to (p. 221). Thin beds of limestone in shales may be formed from confluent concretions. Sometimes concretions are full of radiating veins which, when the outer layer of the concretion

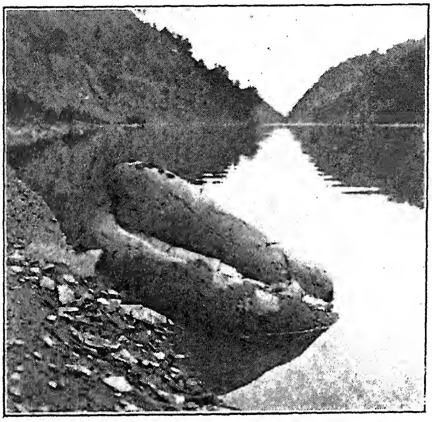


FIG. 478. — Large concretion of the Septarium or "Turtle Stone" type, weathered out of the shale banks (Upper Devonian) on the Genesee River. Others are seen forming bands in the shale bank. (See also Figs. 161 *a*, *b*, p. 222.)

is worn away, may weather out in relief. Such concretions are called *septaria* (Fig. 478). The oölites and pisolites, previously discussed, form aggregates of small, regular concretions occurring as separate deposits. Not infrequently concretions are formed around a nucleus, which may be a plant or a shell or other organic structure (Fig. 181, p. 257). In chalk and limestones the concretions are mostly of silica, flint, and chert (Fig. 162, p. 224), and in sandstones they often consist of iron-cemented sand (Fig. 479).

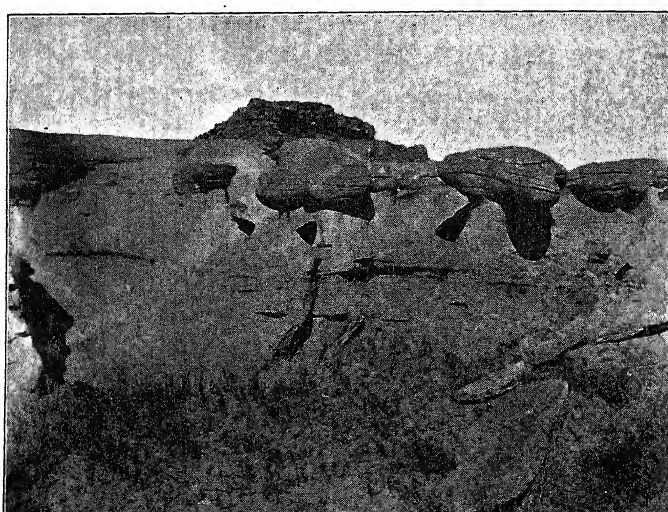


FIG. 479. — Concretionary masses of sandstone (Laramie formation), southwest of New Castle, Wyo. (Darton, photo; from U. S. G. S.)

Varieties of Clastic Rocks

As we have seen, the texture of clastic rocks is their most evident characteristic, as seen in fragments or hand specimens. Hence it is usual to divide clastic rocks first upon a textural basis, and this is threefold as shown above. The more common types of each of these textural groups may now be reviewed.

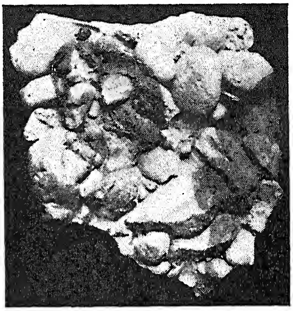


Fig. 480. — Conglomerate (reduced). (B. Hubbard, photo.)

Rubble Rocks or Rudytes

(Texture Rudaceous)

These are the clastic rocks in which the prevailing size of the fragments is larger than that of a sand grain, or in general larger than 2 or 2.5 millimeters. Two main varieties are recognized, as follows:

Conglomerates (Fig. 480). — These are composed predominantly of rounded fragments, generally well water-worn, and most commonly of river or seashore origin. In size the fragments may range from pebbles of the dimensions of peas to large boulders. Some parts of the Old Red Sandstone of Scotland are composed almost wholly of well-rounded boulders, mostly of the size of a man's head. Such rocks are generally spoken of as *boulder conglomerates* (Fig. 481). When the pebbles are few and scattered among sand grains, the rock is called a pebbly sandstone. When the pebbles are very small the rock is called a *grit*. In the decomposition of certain basic igneous rocks, such as basalts, etc., a mass of rounded residual boulders is left (see p. 397), and these may remain piled together in their original position separated by decomposition sand. When

Fig. 481. — Boulder conglomerate. Old Red Sandstone (Devonian) at Oban, Scotland. (Photo by author.)

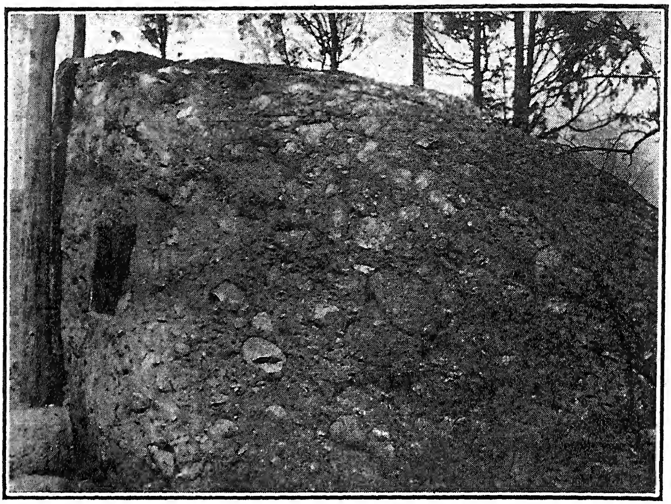


FIG. 482. — Roxbury Pudding-stone, Franklin Park, Boston, Mass. (P. L. Grabau, photo.)

FIG. 483. — A breccia. Devonian limestone which has been broken into angular fragments which have then become recemented into a solid rock — a typical breccia. Iowa. (After Diller, U. S. G. S.)

close-piled, their structure is spoken of as a *cannon-ball structure*, and the rock is called a *residual boulder conglomerate* (*atmoclastic*) (Fig. 331 *a*). Conglomerates of small pebbles may be well stratified, and may show cross-bedding and other structures. Boulder conglomerates generally show little structure.

According to the composition of the pebbles, we may have *quartz conglomerates*, *arkose conglomerates*, *limestone conglomerates*, etc. Examples of these have already been cited. Many conglomerates are, however, *heterogeneous*; that is, the pebbles are composed of a variety of material — granite, gneiss, sandstone, etc. Sometimes conglomerates are formed mostly of one kind of such material. Thus we may have granite conglomerate, volcanic (lava) conglomerate, sandstone conglomerate, etc. According to the nature of the cementing material, we may have quartz-sand conglomerates, calcareous conglomerates, argillaceous conglomerates, ferruginous conglomerates, etc. When the pebbles (generally large) and the cementing mixture between them show little gradation and a marked contrast, the name *pudding-stone* is often applied (Fig. 482). If the pebbles are formed of worn organic structures, we may have coral-conglomerates, shell-conglomerates, etc. Finally, there is the artificial conglomerate or *rubble concrete*, so extensively produced by man.

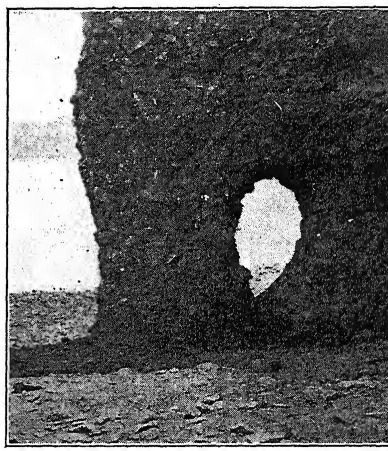


FIG. 484. Projecting cliff of volcanic agglomerate, tunneled by waves along a joint fissure. North shore, Bay of Fundy, Nova Scotia. (G. W. Stose, photo.)

Breccias. — This term is applied when the fragments are angular, showing little or no evidence of water wear (Fig. 483). The principal types of breccia are the *fault breccia* (an autoclastic rock) (Fig. 32, p. 80), the *talus breccia* (an atmoclastic rock), and the *volcanic breccia* or *volcanic agglomerate* (Fig. 484), formed around and in volcanic vents (pyroclastic). A glacial breccia may also be produced, but generally the fragments of a glacial till are scratched and polished. Such a rock when consolidated forms a *tillite* (p. 508). In deposits formed from glacial moraines and outwash material, the pebbles and boulders are commonly well worn, forming a glacial conglomerate.

Sandstones or Arenytes

(Texture Arenaceous)

When the prevailing size of grain of a clastic rock falls between 2.5 and 0.05 millimeters, the rock is said to have an arenaceous texture, and is called a sandstone or *arenyte*. Generally the term sand-

FIG. 485. — Ledge of Oriskany sandstone, Pennsylvania. The rock is a pure quartz sandstone covered by talus from higher sandstone masses. It is quarried here for glass-making under the name Juniata glass sand.

stone is restricted to such rocks in which the grains are chiefly quartz. For this reason the term *arenyte* is preferable, since it implies nothing but textural character. According to origin, composition, and structure a number of common types are recognized.

Quartz Sandstone. — This is the common type in which quartz grains prevail. Many varieties occur determined by the nature of the cementing material. When this is oxide or hydrate of iron, a *ferruginous* sandstone is produced; when carbonate of lime, a *calcareous* sandstone is formed; when much clay is present, the rock is an *argillaceous* sandstone. When pure it is valued for glass-making, as are the Sylvania and the Oriskany sandstones (Fig. 485).

Quartzite. — This is a quartz sandstone in which the grains have become enlarged by the deposition around them of new quartz in such a way as to form a crystallographic continuation of the older quartz. The pores are completely filled and the rock becomes a hard, very resistant mass. (Example: Potsdam quartzite of Ausable Chasm, N. Y.) Quartzites are frequently placed among metamorphic rocks. (See Fig. 373, p. 455.)

Freestone. — This name is given to a quartz sandstone in which the grains are loosely held together, so that they will readily yield to the graver's tools. This is commonly due to the fact that the grains are bound together only by pressure. (Example: Ohio freestone.)

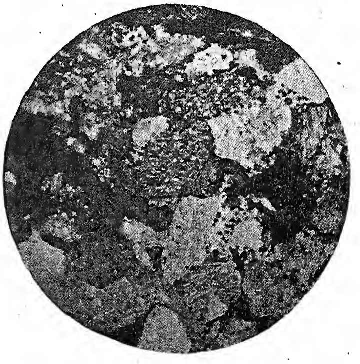


FIG. 486. — Micro-photograph of a thin section of Hudson River Bluestone. The clear grains are quartz, the rest of the field is made up chiefly of secondary derivatives from the original feldspars and ferromagnesian minerals, and of clastoliths. (Photo made and contributed by C. P. Berkey.)

Brownstone. — This is a highly ferruginous quartz sandstone in which the grains are generally coated with iron oxide. It has been extensively used for building purposes. (Example: Connecticut Valley brownstone.)

Bluestone, Flagstone. — This is a highly argillaceous sandstone of even texture and bedding. Commonly the argillaceous material of the cement has been altered to the mineral sericite (Fig. 486). It is probably in most cases the product of ill-assorted sediments in lagoons and lakes near the mouth of a river. Such rock is much used for flags and sidewalk curbings. (Example: Hudson River Bluestone.) (Fig. 487.)

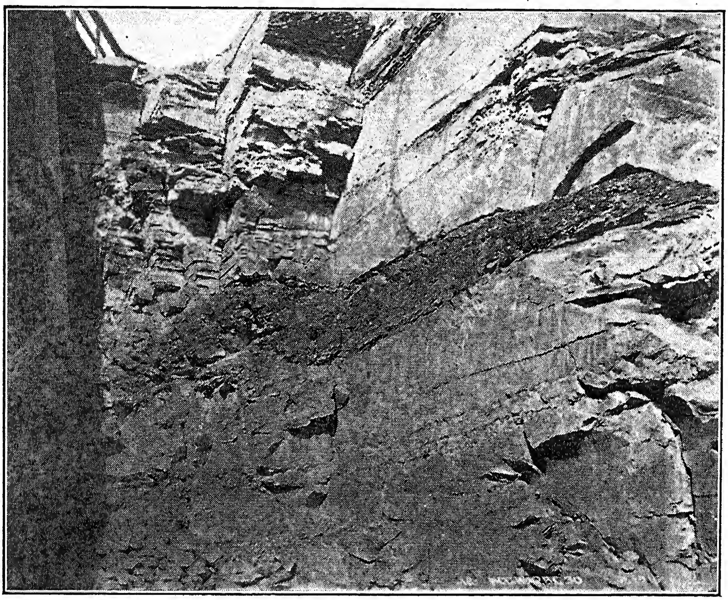


FIG. 487. — Ledge of Hudson River Bluestone, showing solid layers of bluestone alternating with shaly beds. Near Kingston, N. Y. (Photo by C. P. Berkey.)

Graywacke. — This name is applied to an impure, highly argillaceous sandstone of variable composition, texture, and structure. Generally fragments of other clastic rocks are present. The name has been widely used in the past for all the harder argillaceous sandstones of the older geological systems. (Example: Silurian graywackes of England.)

Arkosic Sandstone. — A sandstone in which much feldspar is present. This may range from unassorted products of granular disintegration of fine or medium grained granite (recomposed granites or pure arkoses), to a partly sorted river-laid or even marine arkosic sandstone. (Example: Triassic arkose of New Jersey, some beds of the Potsdam sandstone of New York, etc.)

Glauconitic Sandstone. — (Green-sand.) This is a quartz sandstone or an arkosic sandstone rich in glauconite grains. (Example: Green-sand of England, and of New Jersey and Maryland.)

Lime Sandstone (Calcarenyte). — Arenytes in which the grains are largely or wholly composed of carbonate of lime are called calcarenytes. They are common around coral reefs, and many of the common "limestones" of the various geological formations are really calcarenytes. (Example: Coral sandstone of Bermuda.)

Eolian Sandstone. — Sandstones in which the eolian origin can be recognized in small specimens, either by structure or by character of grains, are referred to as eolian sandstones. They may be pure quartz (Example: Sylvania sandstone) or pure lime. (Example: eolian coral sandstone of Bermuda.)

Volcanic Sandstone or Ash Rock (Volcanic Tuff). — This consists of the material of arenaceous texture produced by volcanic explosions. It is recognizable both by its structure, which is often porous, and by the composition and form of the grains. The rock is generally called a volcanic tuff, but this term is also applied to the finer-grained varieties, which in reality are *lutytes* (Fig. 488).

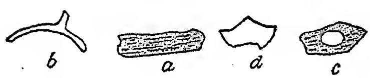


FIG. 488. — Fragments of volcanic glass in tuff as seen under the microscope $\times 50$. *a*, minute particle of pumice; *b*, curved wall of a broken bubble; *c*, small vesicle still complete and surrounded by tubular glass; *d*, interstitial glass between bubbles not tubular. (After Diller, U. S. G. S.)

Mud-stones or Lutytes

(Texture Lutaceous)

When the dominant material of a clastic rock consists of grains less than 0.05 mm. in diameter, the rock is a mud-stone or lutyte. Clay is a common constituent of such a rock, but may be largely or wholly wanting, and the rock may consist of quartz-flour or in part or entirely of limestone flour, or of lime mud. It may also consist of very small wind-transported or water-worn shells of Foraminifera, etc., and of fragments of these. Some of the common types are:

Claystones (Argillutytes). — Rocks in which much clay is present or which are largely composed of clay. Sometimes these are bound together by iron carbonate, forming clay iron-stones, generally of a concretionary character. In large typical masses clay rocks show no regularity of splitting.

Shale. — Mud-rocks containing much clay and splitting into thin layers with curved surfaces parallel to the bedding are called shales. Many shales or similar thin-bedded mud-rocks contain much carbonaceous material, in the form of disseminated coaly matter, or they are saturated with oil. Such shales are called *carbonaceous shales*, *coal shales*, *oil shales*, or *black shales*. When extremely rich in carbonaceous material they are called *pyroschists* and form a transition to coal. Carbonaceous shales generally split with smooth surfaces. Shales may also be highly fossiliferous, when they are generally calcareous. (See Fig.

473, p. 570). *Pyritiferous* shales contain much scattered iron pyrite, which weathers to iron hydrate on exposure, and causes the splitting of the shale. *Silicious* shales contain much quartz-flour and are apt to split into irregular pencil-like and other forms of fragments on weathering. *Red* shales are colored by finely disseminated iron oxide.

Slates. — These are more or less metamorphosed mud-rocks, the metamorphism being due to compression. As a result the slates split into thin layers on weathering or under properly applied force, but this splitting is seldom parallel to the bedding. (Example: roofing slate.)

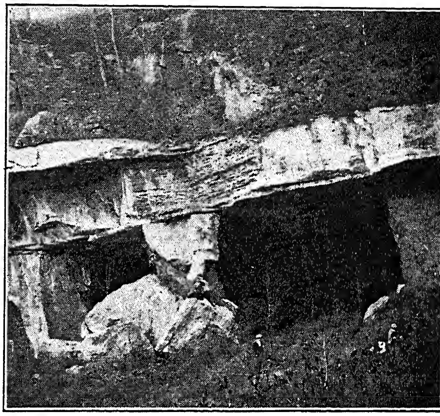


FIG. 489. — An abandoned quarry in natural cement rock or water-lime. The pillars which support the roof are remnants of the water-lime. Rondout, N. Y.

Lime Mud-rocks (Calcilutytes). — These are common around coral reefs, and many old limestones are of this character, having been formed from lime-flour generally deposited in the sea or near its border. Sometimes such rocks show mud-cracks, ripple-marks, and other structures. When alumina and silica are present a *water-lime* or natural cement rock is produced (Fig. 489). Pure lime mud-rocks form the famous lithographic stone of Solnhofen, Bavaria. Rocks of this type often preserve organic remains in wonderful perfection, as is seen in the ancient birds with their feathers preserved and in the dragon flies and other organisms for which the lithographic stone has become famous.

Quartz-flour Rock (Silicilutyte). — Rocks composed apparently largely or wholly of quartz-flour are known. They have a very fine and uniform grain, and furnish smooth and hard surfaces. They are excellent for hone-stones and for polishing, etc. The Arkansas Novaculite appears to be such a deposit, but may be a chemical precipitate.

CHAPTER XIX

DEFORMATION OF THE ROCKS OF THE EARTH'S CRUST

All rocks are subject to deformation after they have come into existence. These deformations disturb the original arrangement of the material of the rock, and modify the original structure which the rock assumed in formation. Such changes are of a superinduced nature, and they are produced by forces other than those operative in the formation of the rock, or by these forces acting upon it in a new way. Deformation structures are therefore secondary, as compared with the primary or original structures.

Effects of Deformation

The effects of deformation are of several kinds, the most important being: (1) production of new structures in the rock masses; (2) change in the character of the material (metamorphism); (3) superficial disturbances of the earth's surface (earthquakes); (4) changes in topography (formation of mountains, etc.). In the present chapter we will consider only the changes in structure and incidentally their topographic expression. Metamorphism and earthquakes will be discussed in subsequent chapters.

Types of Deformation Structures

In general we may consider four types of deformations; *viz.* (1) Foldings and warpings of the rocks; (2) fracturing with displacement of rocks, or *faults;* (3) fracturing without displacement, or *joints;* (4) slaty cleavage. Although all rocks are affected by deformation the effects are most readily recognized in the stratified series, and for that reason the illustrations will be taken from these.

Deformation by Folding

Inclined Strata

In the mountain regions of the earth it is generally seen that the stratified rocks lie in positions deviating markedly from the horizontal (Fig. 490), the latter, as we have learned, being the approximate position in which they are deposited, barring minor local variations as in deltas, around coral reefs, etc. It is true that in some mountains, as in the Catskills, parts of the Rocky Mountains,

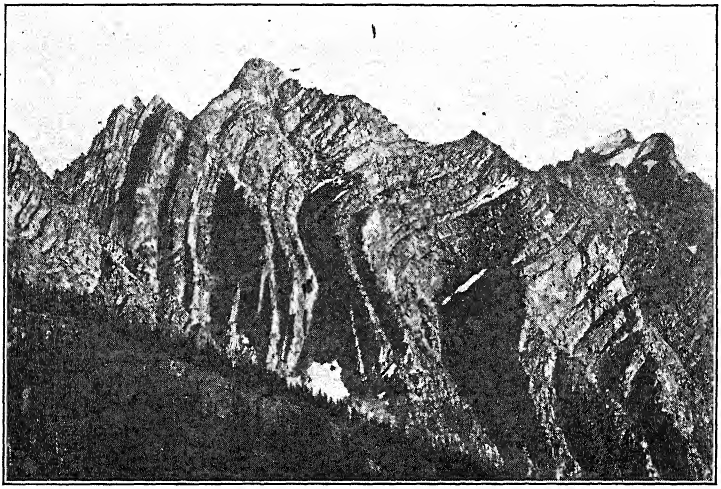


Fig. 490. — Folded strata south of Heaven's Peak, Livingston Range, Montana. (Limestones and argillites of Algonkian age.) Vertical range 2000 feet. (U. S. G. S.; courtesy of D. W. Johnson.)

and elsewhere, the strata may still appear horizontal, but this is rather the exception than the rule. Again, there are regions of the earth, such as eastern New York and New England, numerous areas in Great Britain, Ireland, and parts of the northwestern continent of Europe (Belgium, Northwest Germany, etc.) (Fig. 491), where the strata are not horizontal, although the regions are not now mountainous. Such regions may generally be considered as the sites of former mountain ranges, which have long since been worn away, leaving only their stumps exposed in what is now level or undulating country. In such regions the most general aspect of the strata is that of rising at an angle or vertically from the surface and ending abruptly in the air, and their appearance may be compared

with that of the leaves of a book standing on end or resting in an inclined position. This comparison is, however, apt to mislead, because the leaves of the book are unrelated to the base on which

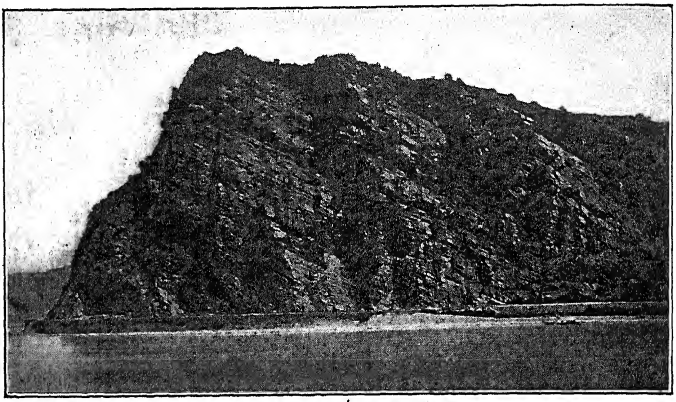


FIG. 491. — The Lorelei rock on the Rhine, formed by inclined Devonian shales and sandstones. The summit of the cliff is a part of the peneplane which has beveled all the strata of this region. (See Fig. 601.)

the book rests. A better illustration of the simplest form of inclined strata is furnished by the metal sheeting of a nearly flat roof, when this sheeting is bent up at one end to form a leader or gutter for the rain water. The inclined strata represent the bent-up portion of this sheeting, the continuation in the horizontal or slightly sloping part being covered. For it must be clearly understood that inclined strata do not continue downwards into the earth with the same inclination for an indefinite distance, but that below the surface they either bend upward again, or in the simplest case assume a nearly horizontal position.

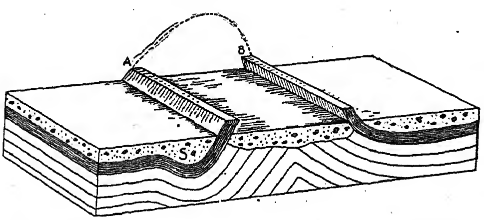


FIG. 492. — Diagram to illustrate the underground extension of inclined strata which crop out on the surface, and the former relationship of the two inclined beds A and B; S, soil.

This is illustrated in diagrammatic manner in Figure 492 at A, where the inclined bed, rising above the surface of soil (s), is seen to be merely the bent-up portion of the bed which beneath the surface changes again to the horizontal.

Moreover, it is obvious that the upper edge of the inclined bed, which now ends in the air, was not its original end but that it is the cut or eroded edge of a formerly much more extensive bed which continued beyond the present point of outcrop (in our diagram to the right) for an unknown distance, as suggested by the dotted lines. Indeed, it often happens that the continuation of the interrupted bed, recognized by its character, its fossils, or otherwise, is found again at another point (in our diagram farther to the right), where it may be represented by another inclined layer descending into the earth in the opposite direction. In that case it is evident that the

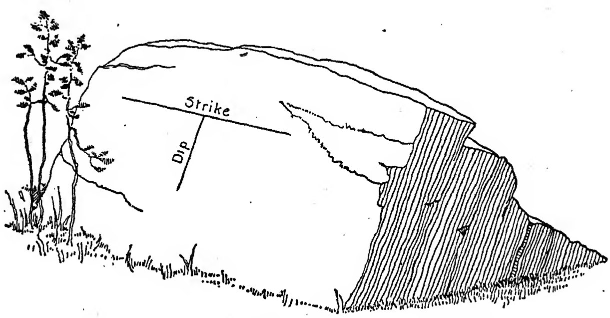


FIG. 493. — Diagram illustrating the relationships of dip and strike of the inclined strata of an outcropping series of ledges. The strike is represented by the line parallel to the horizon (horizontal line); the dip by the line at right angles to the strike.

two outcrops of inclined layers are parts of an arch, the top of which has been cut away by erosion. Inclined layers ending in the air may be produced in other ways (faulting, etc.), but in practically all such cases the inclined part visible is only a portion of a much more extensive bed which continues horizontally or otherwise in one direction and the cut-off edge of which was formerly continuous in the other direction.

Dips. — In the study of the deformational structures of rocks it becomes necessary to measure the amount of inclination of the strata and the changes from place to place. The angle of inclination from the horizontal is called the angle of dip (Fig. 493), and it is measured by an instrument called the *clinometer*.

A simple form of clinometer can easily be made by any one. A piece of cardboard or wood with parallel sides, or the inside of a firm note-book cover, forms the foundation. A graduated semicircle of paper or metal is then fastened to this, so that the ends of the semicircle are on a line parallel with the upper and

lower edges of the supporting board. In the center of this line the end of a thread is fastened (by a pin or through a hole in the board and a knot in the thread), and a small weight is suspended at the other end in such a way that

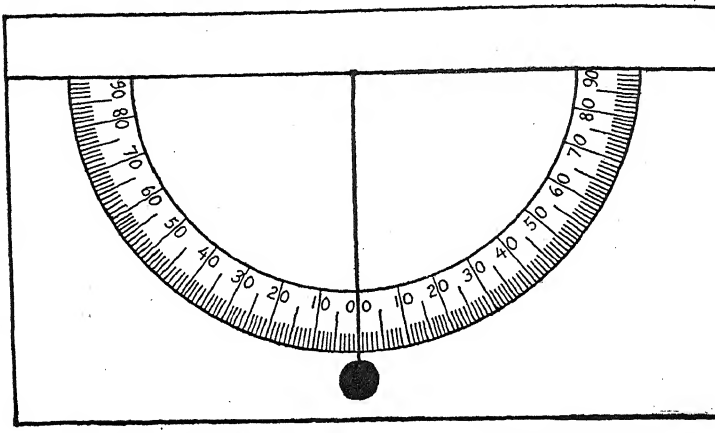


FIG. 494 *a*. — A home-made clinometer. (For description see text.)

it hangs below the arc but still above the lower edge of the supporting board (Fig. 494 *a*). If the work is properly done, the thread should cut the middle of the graduated semicircle when the lower edge of the board rests upon a horizontal surface. This point is marked zero. When the lower edge of the board (or the upper, which is parallel to it) rests against a vertical plane, the string should cut either end of the arc, and this is marked 90°. If the surface on which the clinometer is placed slopes halfway between these two extremes, the string cuts the semi-circle at a corresponding point, and this is marked 45°. The other divisions are marked accordingly. Those who desire may obtain elaborately constructed clinometers, but the greater accuracy of observation with them will scarcely be of much value because of the almost constant variation in dip from point to point.

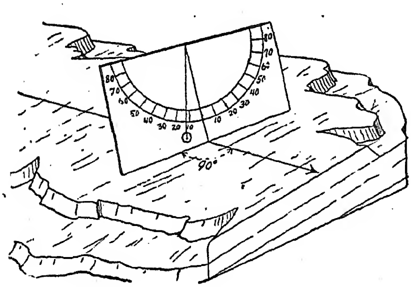


FIG. 494 *b*. — Diagram illustrating gently inclined strata, with the clinometer in proper position to measure the dip at right angles to the strike. (Drawn by Mary Welleck.)

Strike. — The intersection of an inclined bed with a horizontal surface is called the *strike* of the outcrop (Fig. 493), and its direc-

tion is measured by a compass, the dial of which is graduated to degrees. Thus if this line of intersection extends in a direction 30 degrees east of north, the strike is recorded as N. 30° E. (or in exceptional cases S. 30° W.). The dip is then recorded as either east or west, though in the case cited it would really be north of west or south of east, because it is at right angles to the line of strike. Thus a record of strike N. 30° E. and dip 25° W. means that the angle of dip is 25° to the westward, but that the actual direction of the dip (which is at right angles to the strike) is W. 30° N. (or N. 60° W.). Upon a map these facts are recorded by the symbol **T**, the cross-arm of which is placed in the direction of the strike and the stem in the direction of the dip. As the position of the cross-arm upon the map indicates the direction of strike, it is not necessary to record this in figures (except for greater accuracy), but the angle of dip is recorded opposite the stem of the **T**. Thus if the strike is due north and south, a direction represented by the edge of this page, and the dip is 25° to the west, the symbol would have this position: 25°⊣.

Deflection of Strike. — If the surface on which an inclined stratum crops out is not horizontal, but inclined, it becomes evident, on reflection, that the direction which the outcrop takes upon such a surface is not that of the true strike, but a deflection of the same, the amount of deflection depending on the angle of dip of the stratum and the angle of slope of the surface. Only if the dip of the bed is 90°, or vertical, will the line of outcrops be the same, whatever the slope of the surface. The mode of deflection is illustrated in the following diagram (Fig. 495). *ABCD* represents

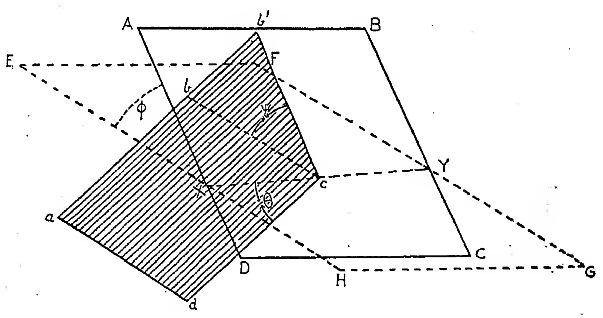


FIG. 495. — Diagram illustrating the deflection of outcrop of an inclined stratum, *a*, *b*, *c*, *d*, from the true strike *bc*, on a horizontal surface (*EFGH*) to a false strike (*cb'*) on an inclined surface, *ABCD*.

the sloping surface of the ground, *EFGH* a horizontal plane; *abcd* is the inclined bed, the direction of true dip of which is indicated by the sides of this bed. It is evident that the true strike is the line *bc*, the intersection with the horizontal plane, whereas, the actual outcrop of this stratum on the sloping surface is represented by the line *b′c*.

The degree of deflection of the outcrop from the true strike can be calculated from the following formula:

$$\tan \psi = \cot \theta \tan \phi, \text{ or } \psi = \tan^{-1} (\cot \theta \tan \phi).$$

when ψ is the angle of deflection; θ the angle of dip of the stratum, and ϕ the angle of inclination of the sloping surface from the horizontal.[1] When it is possible to get the true strike on a horizontal surface and its deflection on a sloping surface, the angle of dip (θ) may be calculated by the following formula:

$$\tan \theta = \tan \phi \cot \psi, \text{ or } \theta = \tan^{-1} (\tan \phi \cot \psi).$$

The illustrations in Fig. 496, *a*, *b* show the manner in which the outcrops of inclined beds are deflected along the sides of valleys with different slopes.

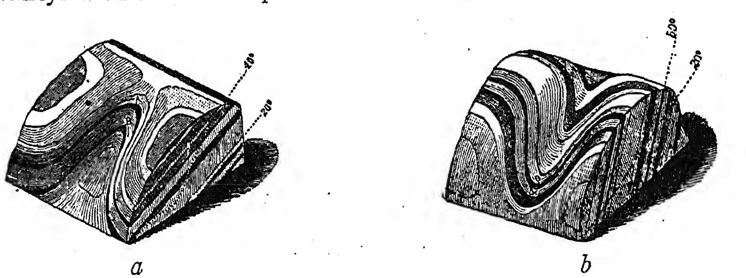


FIG. 496. — Models showing deflection of outcrop of dipping strata on sloping surfaces. *a*, slope of valley 40°, dip of strata 20°; *b*, slope of valley 20°, dip of strata 50°. (After Lyell.)

Relation between Dip and Width of Outcrop. — When a stratum of rock is tilted to the vertical and ends in a horizontal erosion surface, the width of the outcrop on the surface is equal to the thickness of the stratum. If the tilting is less than vertical, the width of the outcrop on the horizontal surface will be greater than the thickness of the bed, and will increase in proportion as the dip of the stratum decreases. From the width of the outcrop and the angle of dip, the thickness of the bed may be ascertained by simple mathematical calculation.

[1] For fuller discussion, see A. W. Grabau, *Principles of Stratigraphy*, pp. 800–806.

Thus in the following diagram (Fig. 497) the width of the outcrop is shown by AB, and the thickness of the bed to be ascertained by AC, which is a line at right angles to the upper and lower surfaces. The dip is the angle ABC, which is one angle of a right-angled triangle of which the length of the hypotenuse, AB, is known and the side AC to be ascertained. This is found by the following formula:

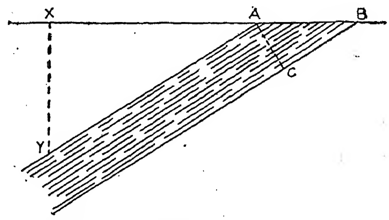


FIG. 497. — Diagram illustrating width of outcrop AB of the bed, the thickness of which is AC; its depth at X is measured by the length of XY.

$$\sin ABC = \frac{AC}{AB},$$

or $$AC = \sin ABC \times AB.$$

If the angle ABC, that is, the dip, is 30 degrees, and the width of the outcrop AB 100 feet, we have $AC = \sin 30° \times 100 = 0.5 \times 100 = 50$ feet. In like manner, if the thickness of a bed and its dip are known while the outcrop is mostly covered by soil, its width for purposes of mapping can be determined by the formula: $AB = \frac{AC}{\sin ABC}$ which, if the thickness, AC, is 50 feet, and the dip 30°, gives $A\,B = \frac{50}{0.5} = 100$ feet. If the bed in question is a coal seam or a water-bearing stratum, its depth below the surface at any point within the belt of outcrop may be determined by noting the distance from the outcrop and the dip. Thus at X the depth $X\,Y$ to the bed is to be ascertained. The distance AX is measured, and the dip $XA\,Y$ determined. Then we apply the formula: $\tan XA\,Y = \frac{X\,Y}{A\,X}$ or $X\,Y = AX \tan XA\,Y$. With the dip 30° and the distance AX 300 feet, we have $X\,Y = 300 \times \tan 30° = 300 \times 0.5774 = 173.22$ feet. If the dip of a water-bearing stratum is 1° and the distance from the point of outcrop 50 miles, while the elevation of the outcrop is 1000 feet above the point at which the well is to be sunk, the depth beneath the surface will be $(\tan 1° \times 50 \times 5280) - 1000 = (.0175 \times 50 \times 5280) - 1000 = 4620 - 1000 = 3620$ feet. This assumes that the dip is constant, which for so low an angle in a region of little disturbance is likely to be the case.

Types of Folds

Three principal types of simple folds are recognized: (*a*) anticlines, (*b*) synclines, and (*c*) monoclines. Each of these has various modifications.

The Anticline. — Arched folds are called anticlines (Fig. 498), and their sides, which are called the *limbs*, dip away from the crest-line or *axis of folding*. Such folds may vary from broad and gentle to sharply ridged arches. If both limbs dip at the same angle,

the anticline is called *symmetrical*, and this type is most characteristic of the Jura Mountains of Switzerland (Fig. 499, *a*), though examples are also found in the Appalachians (Fig. 500) and elsewhere. If one limb has a steeper dip than the other, the anticline is *asymmetrical* (Figs. 499, *b*, 501). In the Appalachian Mountains, the folds of which have their axes extending in a northeasterly direction, the western limb of the anticline is generally steep, often vertical or even overturned, while the eastern limb is more gentle. *Overturned anticlines* (Fig. 499, *c*) are characteristic of some strongly folded regions, and in these one limb comes to lie under the other, and the beds of this limb appear in the reversed order. If the overturning is so extreme that the limbs lie nearly or quite hori-

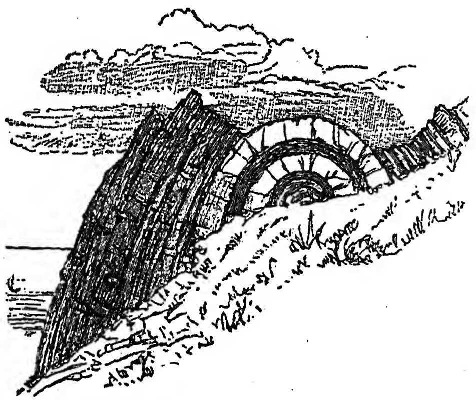


FIG. 498. — A symmetrical anticlinal fold, the top of which has been eroded. Near St. Abb's Head, Scotland. (After Geikie.)

FIG. 499. — Types of folds. *a*, symmetrical anticline; *b*, asymmetrical anticline; *c*, overturned anticline; *d*, recumbent fold; *e*, fan-fold.

zontally, the folds are said to be *recumbent* (Fig. 499, *d*). Overturned strata can often be recognized as such by the position on their surfaces of ripple-marks, rain-prints, foot-prints, rill marks, mud-cracks, and other structures. These will be seen on the under side of overturned strata, while their reverse impressions will appear on the upper side, both being the reverse of the normal position.

Fan-shaped folds (Fig. 499, *e*) are produced when the lower parts of the limbs of the anticline are so compressed that the upper part bulges beyond them on both sides. Such folds are found in the Alps (Fig. 523, p. 606).

When the limbs of the fold are parallel or nearly so, an *isoclinal* folding is produced (Fig. 502). It will sometimes be difficult to

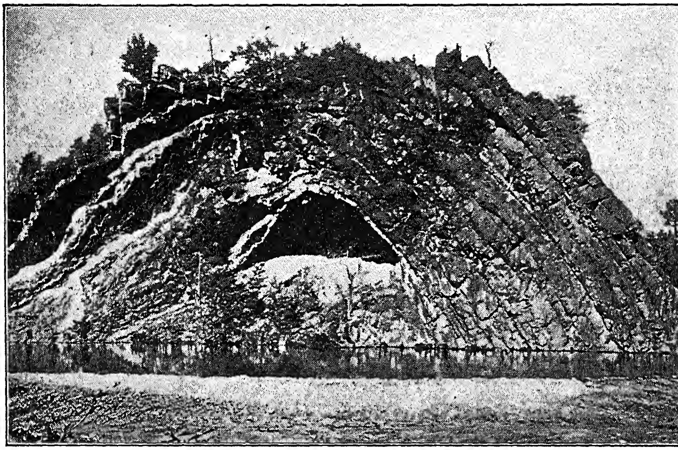


Fig. 500. — Classic arch or symmetric anticline of Upper Silurian red sandstone (in Wills Creek formation), Roundtop, Md. Banks of the Chesapeake and Ohio Canal. The center of the arch has crumbled away, leaving a cavern. (Photo by Stose, from U. S. G. S.)

Fig. 501. — A small asymmetric anticline in Upper Silurian shales and sandstones, High Falls, N. Y.

determine the structure of an isoclinal series of folds if the top has been eroded away. In such a case all the beds may appear to belong to one series (Fig. 502, *a*), unless it can be shown by the charac-

ter of the beds and by their fossils and otherwise that there is a repetition of the same strata in the series. In the diagram (Fig. 502) such a regular repetition of strata is shown, but even here it

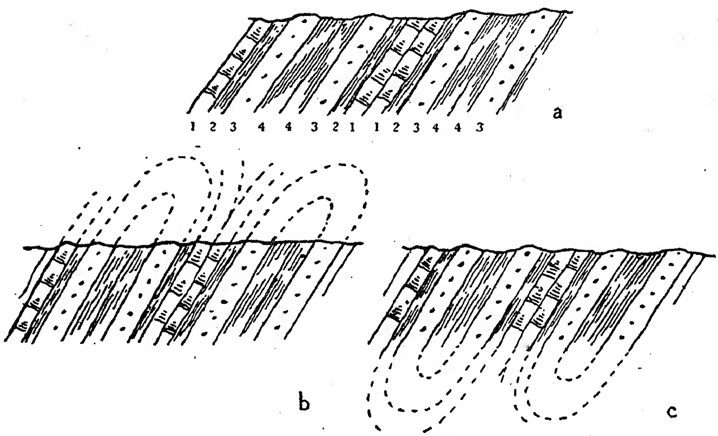


FIG. 502. — Isoclinal folds. *a*, outcrop of strata in which there is a certain repetition of similar beds, which by their fossils or otherwise are recognized to be repetitions of the same strata; *b*, restoration as two anticlines and a syncline; in this case, 4, 4 is the oldest bed; *c*, restoration as two synclines separated by an anticline; in this case, 4, 4 is the youngest bed. (From *Principles of Stratigraphy*.)

is possible to reconstruct the series in two ways, as anticlines with a narrow syncline between (Fig. 502, *b*), or as synclines separated by an anticline (Fig. 502, *c*). The correct reconstruction depends upon the recognition of the relative ages of the beds, the older being at the centers of the anticlines, and the younger at the centers of the synclines. If this cannot be determined, recourse may be

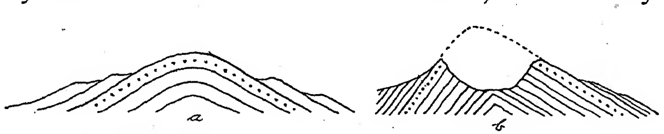


FIG. 503. — Eroded folds. *a*, Symmetrical anticline, from the axis of which the higher beds have been eroded down to a harder stratum; *b*, breached asymmetrical anticline, the hard stratum forming two opposing uniclines.

had to structures such as ripple-marks, mud-cracks, etc., which will indicate the upper and under sides of the strata. It is apparent that the upper sides of the strata will be on the inside of the syncline but on the outside of the anticlines.

In general, when folding is pronounced, the beds in the axial part of the anticline as in that of the syncline (see beyond) are thickened, while those of the limbs become thinner. This reaches its extreme in fan-folds, but is also observable in others. It implies a certain amount of transference of the material of the beds from the limbs to the axes.

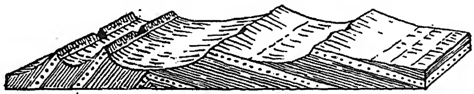


FIG. 504. — Block-diagram of the uniclinal ridges of the Appalachian type; the original anticline from which the uniclines are cut was asymmetric, with the steeper limb on the west.

Small anticlines may be complete, but the larger structures of this type have commonly suffered erosion along their tops. This is comparatively slight in the Jura Mountains, where large anticlines are still nearly complete with only their upper layers partly removed from the axis (Fig. 503, *a*). In the Appalachian Mountains, on the other hand, the anticlines have been for the most part deeply dissected so that a depression or valley lies at their axes and the cut ends of the limbs end in the air (Figs. 503, *b*, 504). If the folds of the original anticlines consist of alternating hard and soft strata, a series of parallel ridges formed by the hard layers, and valleys formed on the soft layers may be produced as the result of erosion. The beds of corresponding ridges will dip in opposite directions. This is of common occurrence in the Appalachians,

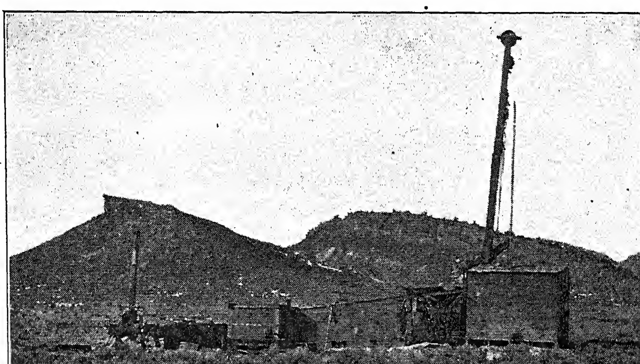


FIG. 505. — Uniclinal ridges formed by the erosion of an anticline. Utah. (F. J. Pack, Photo.)

and to such erosion remnants of anticlinal folds, the name *unicline* is applied (Fig. 505). (See further, Chapter XXII.)

Pitch of Axis of Anticline. — The axis of the anticline may continue in a horizontal position for a long distance (sometimes for

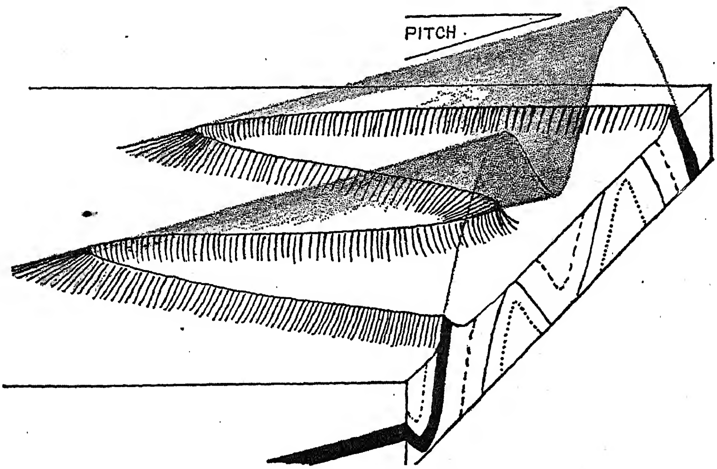


FIG. 506. — Diagram showing pitching folds and the topography formed by their erosion. (Drawn by F. K. Morris, *Military Geology.*)

more than a hundred miles), but eventually it descends or pitches into the ground and the fold dies away (Fig. 506). When the pitching axis of an anticline is planed across horizontally by erosion,

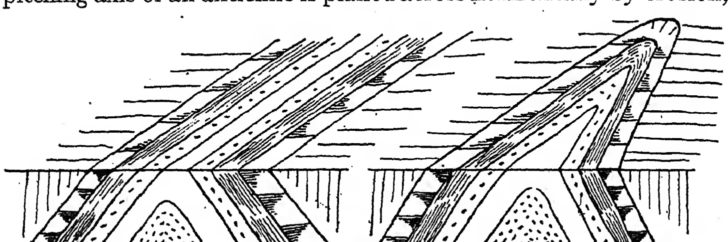


FIG. 507. — Eroded anticlines with horizontal and with pitching axes. In the first case the strata crop out in parallel series, the oldest at the center; in the second case they converge in the direction of pitch. (From *Principles of Stratigraphy.*)

the upper ends of the several beds will be seen to converge in the direction of the pitching and eventually to meet (Fig. 507). When some of these beds form ridges, these too meet and enclose a semicircular canoe-shaped valley (Fig. 508).

Domes. — Anticlines with very short axes are called *domes*. The length of the axis may be several times the transverse diameter of the dome, or it may nearly equal it, but domes are seldom quite circular in basal outline. Such domes may be pronounced, with steeply dipping sides, as in the case of the Black Hills of South Dakota, or

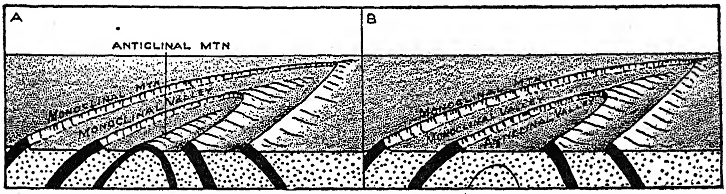


FIG. 508. — Development of concentric ridges in anticlinal structures. *A*. An anticlinal or cigar-shaped mountain results from the position of the hard rock. *B*. The anticlinal mountain *A* is replaced by an anticlinal valley because of the position of the strata. (After A. K. Lobeck.) Note that the cut faces of the ridge-forming strata face inwards. These ridges are "monoclines of erosion" or "*uniclines*."

they may be so gentle that the dip of the strata is scarcely perceived. The latter are by far the more common, and of them the Cincinnati dome may serve as an example. On account of their large size and gently dipping strata they are recognized only when plotted upon a geological map.

Anticlinoria. — A mountain mass composed of a number of anticlines may have these so arranged that they form a part of a larger arch. This compound anticlinal series is called an *anticlinorium.*

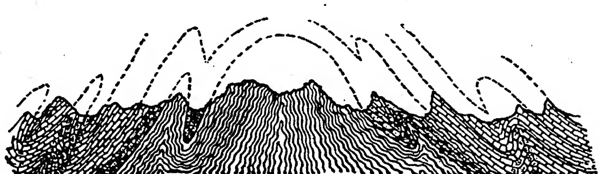


FIG. 509. — Anticlinorium. Generalized section in the Alps. (After Heim.)

Such an anticlinorium may constitute a part of a mountain mass, as in the Alps (Fig. 509); or the central beds may be eroded because these are soft, and so a valley is produced. The Wealden district of southeastern England is such an eroded anticlinorium, the minor foldings being seen in the variable dips of the strata in the center, which, because of the softness of the strata, has generally been transformed by erosion into a valley.

Synclines. — When two or more anticlines occur in a folded system such as the Jura or Appalachian Mountains, they are separated by trough folds or *synclines* (Figs. 510, 511). These are symmetrical

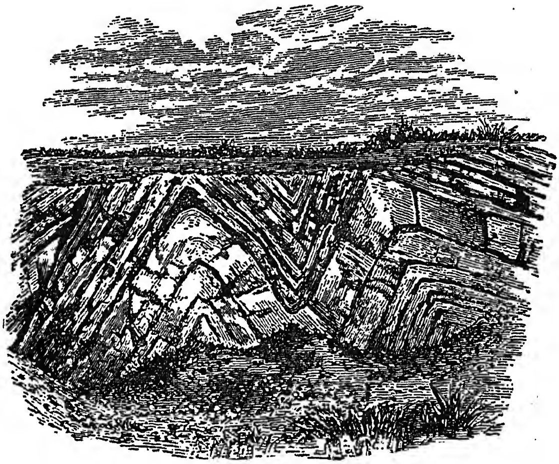


FIG. 510. — Natural section, showing two anticlines and a syncline. The surface is a peneplane cutting across the folds. Scotland. (After Geikie.)

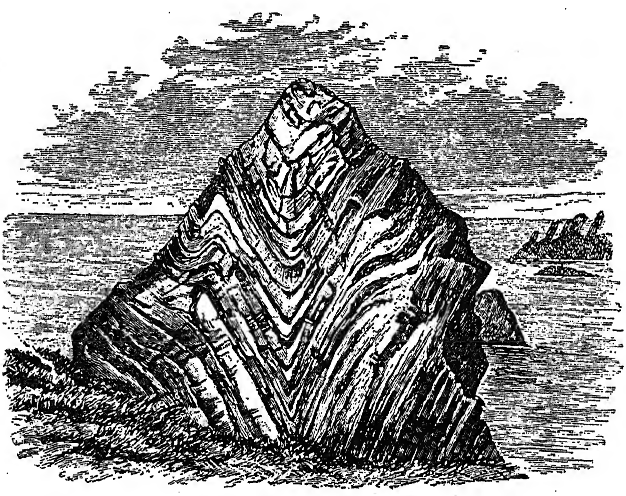


FIG. 511. — Synclinal fold near Banff, Scotland. (Geikie.)

in the Jura but asymmetrical in the Appalachians, corresponding in character to the anticlines. In the Appalachians the eastern limb (or arm) of the syncline is steep, vertical, or overturned, being in

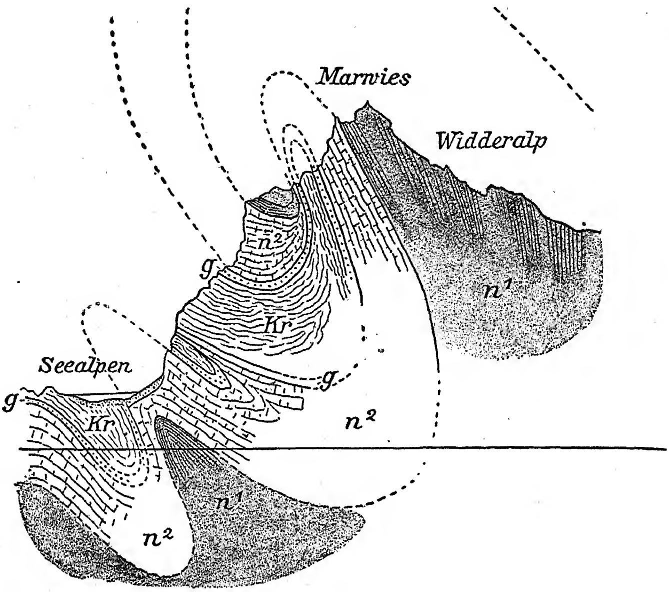


FIG. 512 *a.* — Rapid change in thickness of beds, due to strong folding. n^1, Neocomian; n^2, Schrattenkalk; *g*, Gault; *Kr*, Seewer limestone (Upper Cretaceous). After Alb. Heim. Säntis. (From Kayser's *Lehrbuch.*)

FIG. 512 *b.* — Synclinal fold of Knox dolomite, showing thinning on the limbs of the fold and thickening in the axis. One half mile north of Embreeville, Tenn. (Photo by Keith, from U. S. G. S.)

fact the western limb of the anticline next east. The western limb (or arm) of the syncline, which is also the eastern limb of the anticline next west, has a moderate inclination. In the center of the syncline the beds are usually thickened, as is well shown in the section of Alpine folds in Fig. 512 *a*. It is also seen in the Appalachian Mountains (Fig. 512 *b*). This portion of the fold may also be characterized by numerous smaller folds, this complex when

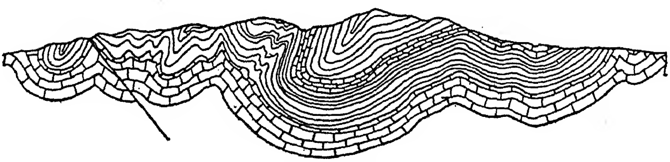


FIG. 513. — Synclinorium. Section of Mt. Greylock, Mass. (After Dale.)

occurring on a sufficiently large scale being called a *synclinorium* (Fig. 513). Synclines may also be overturned and recumbent, and their limbs may be parallel, forming a part of an isoclinal series of folds as in Fig. 502, p. 592.

Topographically, the beds of a much eroded syncline may also form parallel ridges, but the cut edges of these face *outward*, instead

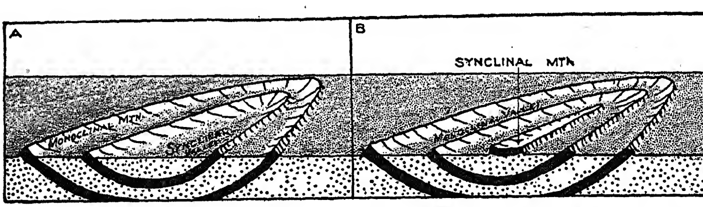


FIG. 514. — Development of concentric ridges in synclines. *A*, a region with synclinal or canoe-shaped folds. In *B* the synclinal valley shown in *A* is replaced by a mountain because of the occurrence of a hard stratum in the center. (A. K. Lobeck.) Compare with Fig. 508, p. 595. Note that the cut edges of the hard ridge-forming strata face outward. The ridges, too, are "monoclines of erosion" or *uniclines*.

of *inward* as in the case of the dissected anticline (Fig. 514). For such ridges the term *unicline* is used. They are also called "monoclinal ridges of erosion."

As the syncline dies out, the axis rises, and in eroded synclines the cut edges of the strata and the ridges which they form converge and finally unite. Thus another series of rimming ridges and canoe-shaped valleys is produced.

By deep erosion of the centers of adjoining anticlines, the center of the syncline may be left standing in relief and a synclinal mountain is produced (Fig. 515, see also Figs. 513 and 514, *B*). Such mountains are not uncommon in the Appalachian and other deeply eroded mountain systems.

Basins. — A syncline with much shortened axis produces a *basin*, which is the reverse of the dome. The majority of basins have their strata so gently inclined that they appear to be practically horizontal. They can be recognized, however, in eroded regions by the fact that the edges of the older or lower strata project progressively beyond those of the younger or upper, while their outcrops form a more or less completely encircling series of bands. Where hard strata are involved, these form rimming ridges with their cut ends facing outward. Such a series of rimming cliffs partly encircles the Paris basin, in the center of which lies the city which gives it its name. The basin in the center of which London lies is another, though less perfect example. In our own country, the Michigan basin, which comprises the whole of the Lower Peninsula, is a typical example. On the west, north, and east of this basin the lowlands cut on the softer strata are partly occupied by the waters of some of the Great Lakes and their embayments (Figs. 516, 517).

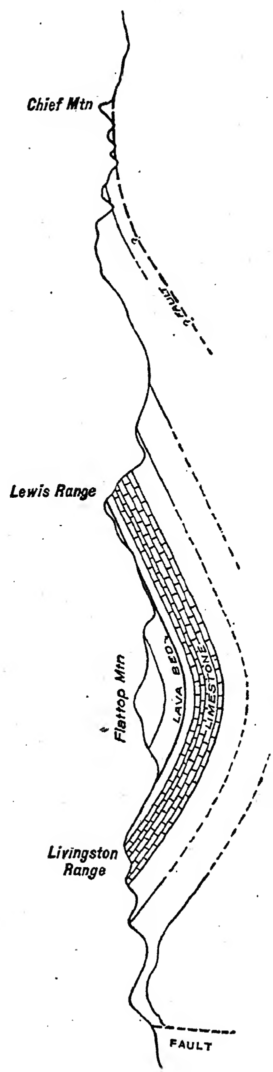


FIG. 515. — Section across the Livingston and Lewis ranges, with Flattop Mountain, a synclinal mountain, and Chief Mountain, a remnant of an overthrust fault block. The strata are more complexly folded than is here shown. (See Fig. 490, p. 583, and Figs. 549 *a*, *b*.) (After Campbell, U. S. G. S.)

The Monocline. — A simple flexure in the rocks in which the beds bend up or downward and then continue in the same direction, is called a *monocline*. Such monoclines are found on the margins of folded areas and in regions of minor disturbance as in the Colorado Plateaus (Figs. 690 *a*, *b*), where they form important structural features. A monocline may pass into a fault as shown in the diagram (Fig. 518 *a*). The monoclines of the Colorado Plateau region (Grand Cañon district) commonly pass into what may be termed an inverted fault, where the upflexed side becomes the downthrow side of the fault, and the downflexed, the upthrow side of the fault (Fig. 518 *b*). In these faults the beds of the upthrow block bend upwards as they approach the fault plane and those of the downthrow block bend downward. This probably indicates two movements, a flexing to the breaking point, and a settling back with faulting, of the elevated block.

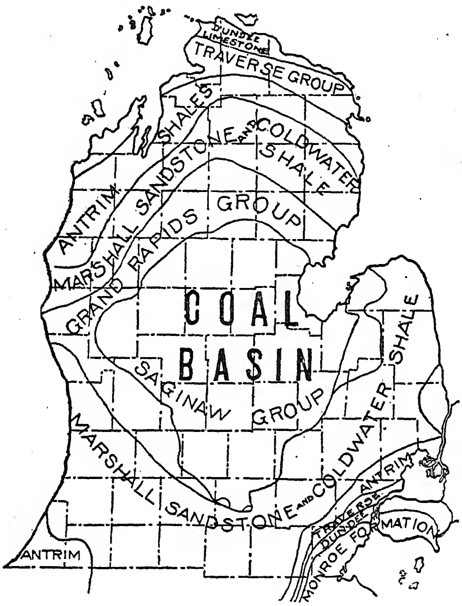


Fig. 516. — Geological map of the Michigan Basin, showing the successive rims formed by the outcrops of the strata around the central coal basin. (Mich. Geol. Survey.)

Relation of Folded Mountain Series to Geosynclines of Deposition

All the larger folded mountain systems appear to be located along regions which were formerly geosynclines of deposition (p. 518). This is shown by the fact that in such folded areas the formations are all of much greater thickness than elsewhere. Several of these may be noted.

The Appalachian Mountains. — These were formed by the folding of the strata which accumulated in the Appalachian geosyncline to a thickness of perhaps 40,000 feet. This geosyncline was bounded

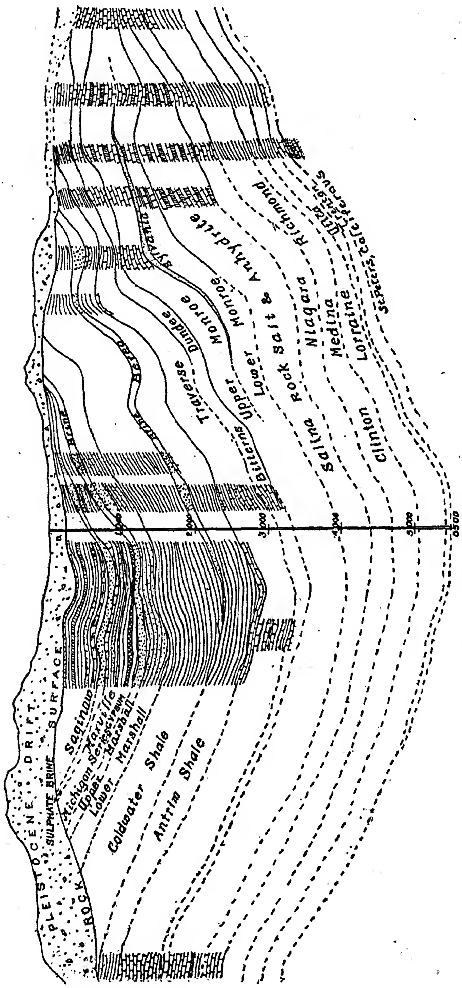


Fig. 517. — Cross-section of the Michigan Basin based on well sections. Owing to the exaggeration of the vertical scale, the folds appear more prominent than they are in reality. For a more diagrammatic cross-section, which emphasizes the topography of the region, see Fig. 622.

on the east by a high more or less mountainous land mass, the ancient Appalachia, from which the clastic material which makes up a large part of the strata was chiefly derived. The series comprises alternating marine and continental beds, but on the whole is rather uniform, and constant subsidence is indicated for the old

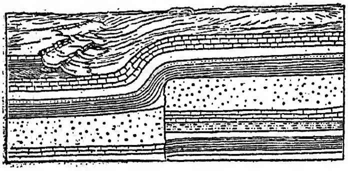


FIG. 518 *a.* — Monocline replaced in the lower strata by a fault.

geosynclinal trough. Folding occurred locally at several periods, but the great folding took place toward the end of the Palæozoic era. This produced the asymmetrical anticlines and synclines characteristic of this system. Because the steep or overturned limb of the anticlines is on the west, it would seem that the movement which produced the folds came from the east, or from the Appalachian old land. The most intense folding is on the east, the next upon the western border (Fig. 519). There are also pronounced overthrusts (see p. 626). Beyond the strongly folded western part minor folds occur, but soon die out, and the strata become approximately horizontal. The force, however, appears to have been transmitted over a great part of eastern North America, with the development of an extensive series of low domes and shallow basins, such as the Cincinnati dome and Michigan basin. Some, or perhaps most, of these had begun to form at an earlier time, probably during one or more of the earlier periods of folding but their most pronounced structure was given to them during the Appalachian folding. It must be remembered that these domes and basins are so large and so gentle that the strata appear horizontal and their dome- and basin-character can be seen only on the

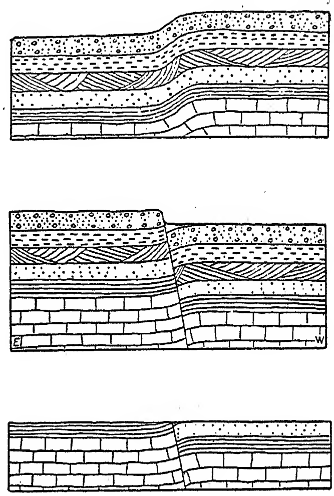


FIG. 518 *b.* — Diagram showing early stages in the development of the Hurricane fault in the Grand Cañon region, — a monoclinal fold develops into an "inverted" fault, the upflexed side becomes the downthrow side, the downflexed the upthrow. Note that the strata at the border of the fault plane bend in the reverse direction of that due to drag along a simple fault. The upper diagram represents the monoclinal flexure; the middle, the faulting; and the lower, the appearance after erosion (peneplanation). This was followed by further movements in the same direction along the fault plane. East on the left. (After D. W. Johnson.)

study of extended areas. Wherever two basins adjoin each other, there is a sharp but small anticline or series of anticlines formed between them, as shown in the lower sections on this page (Fig.

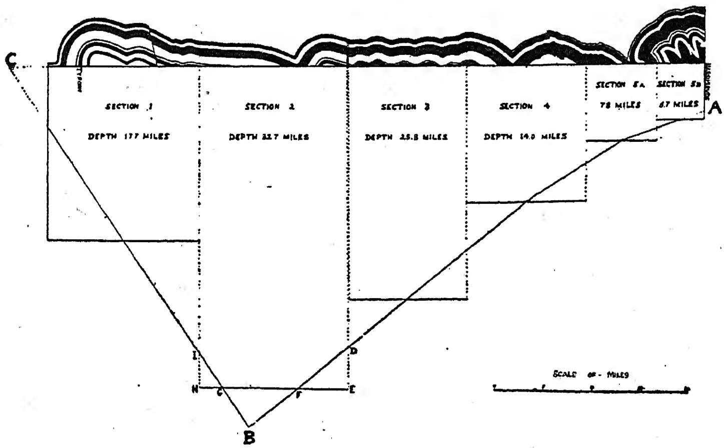


FIG. 519. — Restoration of the Appalachian folds of Pennsylvania between Harrisburg on the east (right) and Tyrone on the west (left), showing the different intensities of folding, and the portion of the earth's crust (*ABC*) affected by the compressive movement. (After R. D. Chamberlin.)

520). In some cases these anticlines have proved favorable for the accumulation of oil and gas. In like manner, a syncline or group of synclines lies between adjoining domes.

The trend of the Appalachian folds conforms more or less to the position of the domes and basins adjoining them, being bowed outward around the basins and inward between them (Fig. 521).

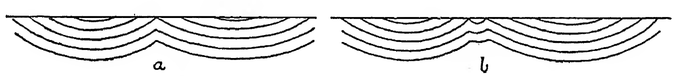


FIG. 520. — Cross-sections of shallow basins, separated (*a*) by a simple anticline, (*b*) by two anticlines and a syncline.

The Carpathians. — As a second example, the Carpathian Mountains of Europe may be cited. These form a semicircular arc, enclosing the basins of Hungary and Transylvania on the north, east, and south, and they are a part of the Alpine system of folds (map, Fig. 522). They are of much more recent origin than the Appalachians, having been formed in Tertiary time. The outline of this arc appears to have been determined by the form of

the geosyncline in which the strata, which became involved in the folds, were deposited. The old land from which the clastic material was derived lay to the north and the east of the present mountain chain, and the sediments were carried toward the Hungarian basin, most of them lodging in the geosyncline, around its outer (eastern and northern) margin.[1] The first folding took place at the beginning of Mid-Tertiary (Miocene) time, and resulted in the formation of mountain chains from the deposits in the geosyncline. The movement was probably toward the Hungarian basin. During

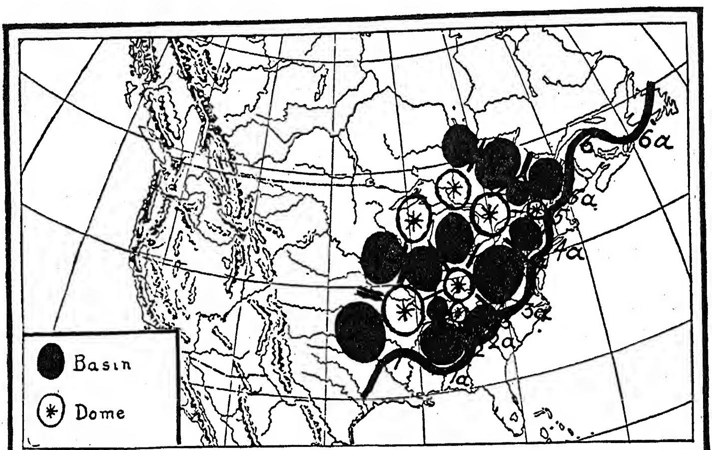


FIG. 521. — Map of the domes and basins of eastern North America, and of the outline of the Appalachian chains. 1–6, land lobes; 1 *a*–6 *a*, sea lobes.

this folding, or probably as a part, if not a cause of it, a new geosyncline came into existence by the sinking of a part of the old land which had supplied the sediments. This sinking occurred along a belt parallel to and outside of (north and east of) the newly formed semicircle of mountains. In this new geosyncline, later sediments, to the extent of several thousand feet, were deposited, these being in large part derived from the newly formed Carpathians. In this geosyncline were also formed many of the important salt deposits of that region. Then came a second folding, this time with a movement toward the new geosyncline (eastward and northward) so that the strata of this geosyncline were thrown into asymmetric anti-

[1] A. W. Grabau, *Geology of the Non-Metallic Mineral Deposits*, Vol. II, Chapter XXXII, McGraw-Hill Book Co.

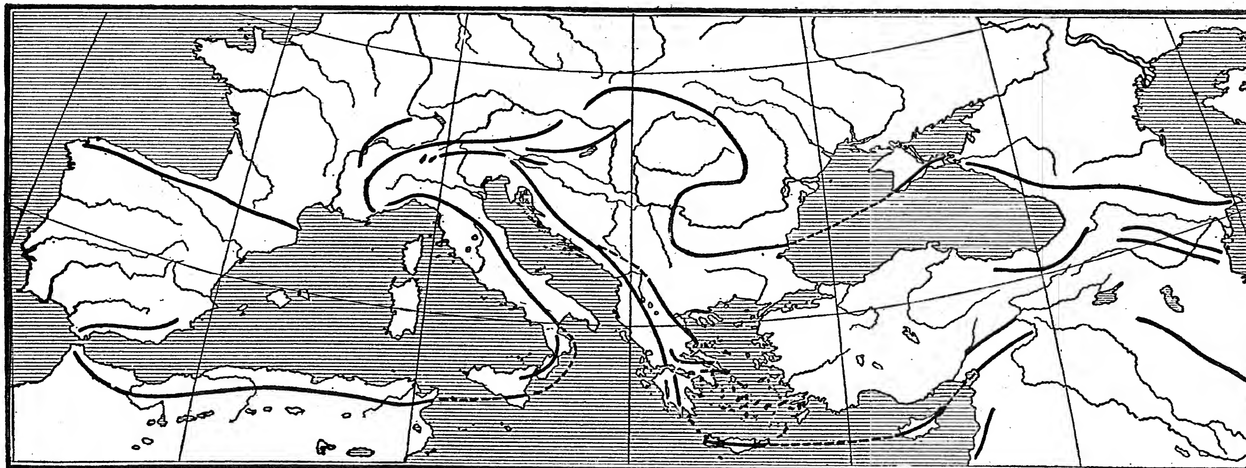


FIG. 522. — The mountain chains of Europe and the neighboring districts. The *Pyrenees* of the Franco-Spanish border continue westward in the *Cantabrian Mountains* of North Spain. The *Sierra Nevada* of southern Spain and the *Atlas Ranges* of Africa are connected by broken lines with the Italian *Apennines*, curving northwestward as the *Ligurian Alps*. On the Franco-Italian border arises the main chain of the *Alps*, curving eastward through Switzerland. The *Jura* chains form a parallel arc to the northwest. From the Danube Valley the Alp chain continues as the *Carpathian ranges* around the Hungarian basin; southwestward in the *Transylvanian Alps* to the Iron Gate of the Danube River; southeastward in the *Balkan Mountains;* and extends through the *Crimo-Caucasian chain* and the Asiatic *Great Balkan Mountains*. North of the Adriatic, parallel to the main Alpine chain, lies the *Bakoni Forest Range*, continuing southward along the east Adriatic coast in the *Dinarian Alps*, to the *Pindus* and *Peloponnesian Mountains* and several eastern branches. From southern Greece through Crete, Cyprus, and Turkey extends a broken line parallel to the northwestern *Anti-Taurus Range*. Other ranges lie between the Black and Caspian seas.

clines, with steep limbs on the east and north or away from the mountains. At the same time, the already folded strata of the earlier Carpathians were folded more intensely, and portions were thrust over toward the Russian regions on the east. Thus the horizontal rocks of Russia and the coal fields of Silesia on the north pass under the folded rocks of the Carpathians, which have overridden them.

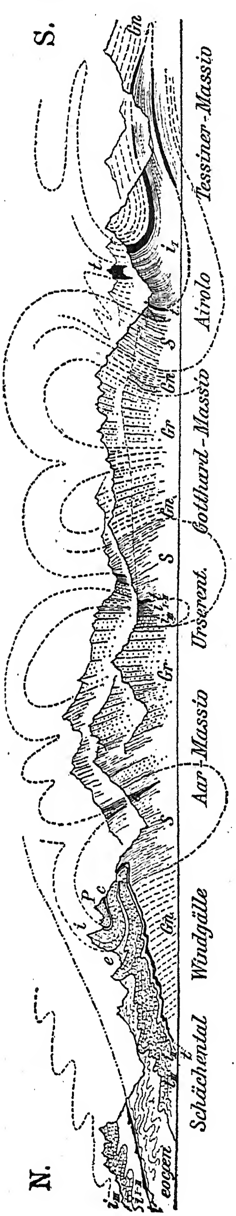


FIG. 523. — North-south cross-section of the St. Gothard Massif, Switzerland, showing the fan-folds. Drawn by Alb. Heim. *Gn*, gneiss; *Gr*, granite; *S*, micaschist and phyllite; *c*, Carbonic; *P*, Permian; *t*, Triassic; *i*, Jurassic; *e*, Eocene. (From Kayser's *Lehrbuch*.)

The movement toward the Hungarian plain during the first folding appears to have affected the rocks of this plain also, by breaking them into a series of blocks instead of developing domes and basins as in North America.

The Alps. — These are among the most complex mountain systems known. The main line forms an arc extending around the plains of North Italy, in general north and south along the Franco-Italian border, and turning eastward in Switzerland and the Tyrol (see map, Fig. 522, p. 605). As in the case of the Carpathians, this arc was outlined by the old geosyncline in early Tertiary time and the form of the old land on the west and north. After deposition of great thicknesses of clastic material, derived from this old land, had taken place in the geosynclines, the first folding occurred at the beginning of Mid-Miocene time. The movement there was apparently toward the Italian region, which was broken into blocks, while the

strata were overturned toward that region. As in the Carpathians, another new geosyncline came into existence in the old land, north and west of the newly formed chain, and in this geosyncline great masses of clastic material, derived from the newly formed Alps, were deposited. Then came the second folding toward the new geosyncline (west and north) so that the strata were folded over in the other direction, while at the same time great blocks were thrust over in this direction. In this manner was probably formed the peculiar fan structure of the Alpine folds (Fig. 523).

Structures Due to Repeated Folding

In the Alps, Carpathians, and other great mountain systems of Europe and elsewhere, at least two periods of folding and perhaps more are recognized, following each other with comparatively short intervals. These two

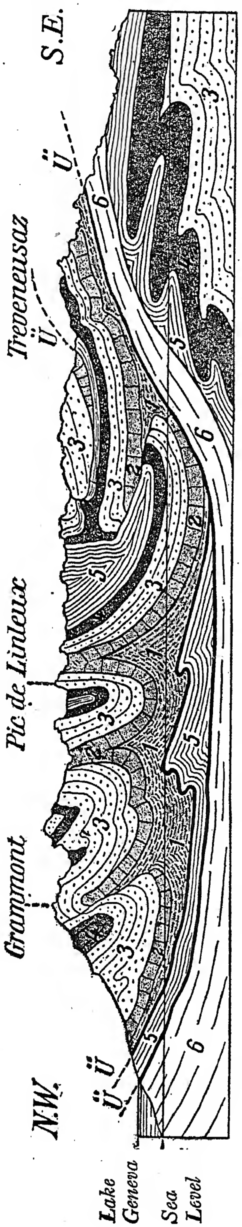


FIG. 524. — Cross-section of a part of the West Alps, south of Lake Geneva, mainly in France. 1 and 2, Triassic; 3, Jurassic; 4, Cretaceous; 5, Older Tertiary (Flysch); 6, Miocene; *U*, overthrusts. (After H. Schardt, from Kayser's *Lehrbuch*.) Note that older Tertiary (5) is overthrust on the younger (Miocene (6)), and is in turn overthrust by the still older Mesozoics (Triassic, Jurassic, and Cretaceous). On the right (southeast) the series is complete and in normal order of succession. Thus it appears that the overthrust has come from the southeast, and belongs to the last stage of deformation (post-Miocene). The overthrust of the Mesozoic upon the older Tertiary apparently belongs to the older folding which preceded the Miocene sedimentation, for it is observed that the older thrust plane is folded, apparently during the second period of deformation. On the right of the section it is seen that the Miocene overlies the older Tertiary unconformably — the strong folding of these and the Mesozoic beds beneath belonging to the older period of deformation.

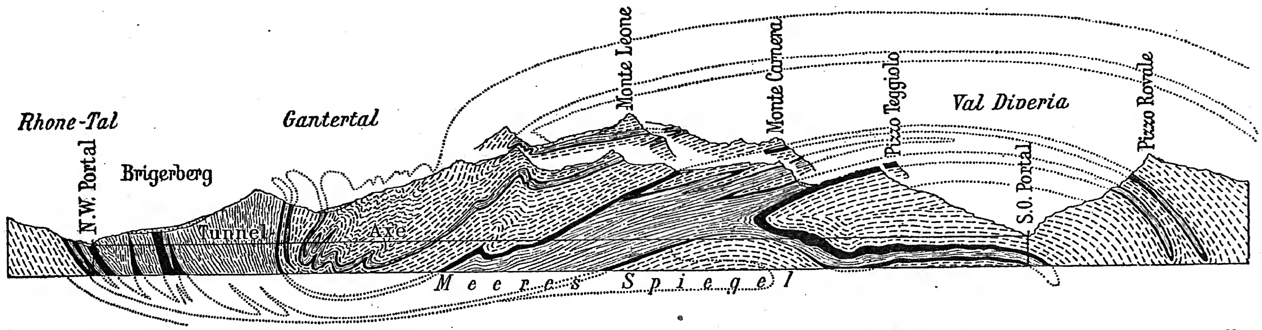


FIG. 525. — Section through the Simplon massif, along the axis of the Great Simplon tunnel from the Rhone Valley, Switzerland (on left), to the Val Diveria, Italy (on right). By H. Schardt, 1902–1906. Scale 1 : 135,000. *Short broken lines* = Archæan gneiss, granite, etc.; *black* = Triassic dolomitic limestone, marble, gypsum, sericite schist; *long lines* = Jurassic limestone, mica schist, etc.; *white with dots* = Quaternary débris. Note that the great overfoldings are toward the northwest, *i.e.* towards Switzerland. (From Kayser's *Lehrbuch.*)

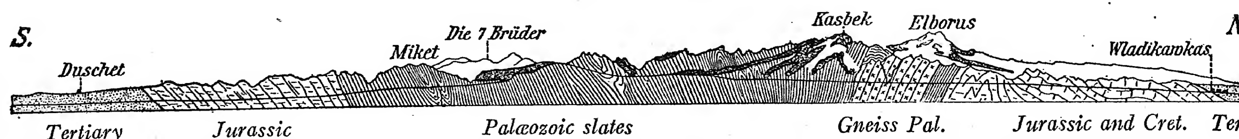


FIG. 526. — Cross-section of the Caucasus along the Grusinian military road. (Alb. Heim.) About 1 : 1,200,000. Dark beds are lava streams. (From Kayser's *Lehrbuch.*)

foldings appear to have been in opposite directions, the last movement being toward the west and northwest in the French Alps (Fig. 524), and toward the north in the Swiss-Italian and Austrian Alps (Fig. 525); while in the Carpathians it was northward in the northern, eastward in the eastern, and southward in the southern portion of the arc. The results of this compound folding have produced extremely complex mountain systems, the complexity

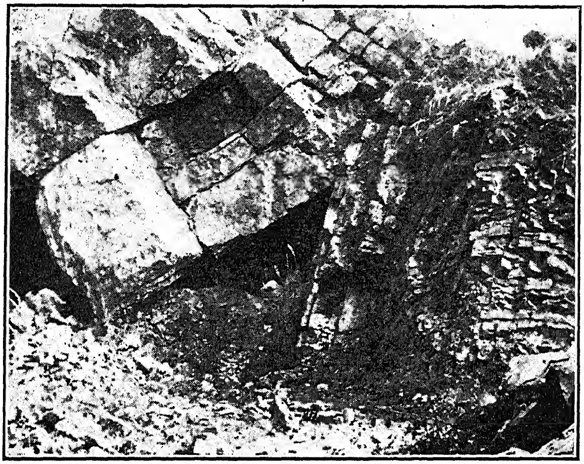


FIG. 527. — Photograph of the unconformity between the Silurian and Ordovician formations on the Vlightberg above Rondout (Kingston), N. Y. On the right are the Hudson River sandstones and shales with a strike of N. 30° W. and a dip of 51° to the northeast. Against the eroded surface of these rest the Upper Silurian limestones (Cobleskill) which strike N. 56° E. and dip 72° to the northwest. The large inclined masses of limestone in the left half of the view are the highest beds of the Silurian (Manlius) which originally had the same inclination as the Cobleskill, the space between these two series being occupied by the Rondout water lime which has been quarried out, after which the Manlius fell over into its present position. (Photo by M. O'Connell.) (See Fig. 528 *a*.)

being increased by great overthrusts. In the Caucasus the folding was very intense, so that all the beds are either vertical or steeply inclined (Fig. 526).

In the Appalachians, where more than one period of folding is recognized, the foldings appear to have been in the same general direction, though in part, at least, with a slight change in strike. Moreover, the movements of at least two of these foldings of which we have positive evidence occurred at long intervals, one near the close of the Ordovician period, the other toward the close of the

Permian, although there were, in some localities at least, others between these. In the intervals between the foldings, extensive erosion of the older folded series took place, after which more strata were deposited upon these eroded surfaces, and the whole complex folded again. Thus a complicated structure was produced, but the complication is less than in the Alps. The illustration on page 609 (Fig. 527) presents the appearance of an outcrop in a hillside above Rondout, N. Y., which shows strikingly the complexity resulting from such double folding. (See also Fig. 528 *a*.)

A bed of limestone, *S*, of Upper Silurian (Monroan) age is seen to have a nearly vertical position. It is part of a thick series which has the same position and represents the western vertical limb of an asymmetric anticline as shown in other sections. This belongs to the last period of folding, which was in general toward the northwest as the strike of this bed is to the northeast. The exposed side of this bed is its upper surface. Resting against it on the right is a series of sandy beds (*O*), which apparently dip at an angle of about 50° to the northeast, or in the direction of strike of the limestone bed. These belong to the Middle Ordovician series. From observation of ripple marks, mud cracks, and raindrop impressions, on the overhanging portions of the cliff and other exposures near by, it appears, however, that these beds are completely overturned; that, in fact, the overhanging surface is the top of the beds (see p. 550). This apparent complication is simplified when we attempt to restore the conditions which existed here before the last folding. Turning the bed (*S*) back to the horizontal, we find that the apparent dip of the Ordovician beds (*O*) is really their strike as it existed after the first folding, and that their dip was vertical, this being transformed into the present strike of these beds by the second folding (Fig. 528 *b*). By this return to the conditions before the

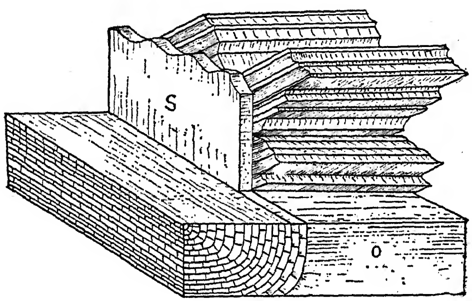


FIG. 528 *a*.—Diagram showing the relationships of the Ordovician sandstones (*O*) to the Silurian limestones (*S*) on the Vlightberg at Rondout, N. Y. Shown in Fig. 527.

second folding, it is seen that the strike of the first set of folds was more nearly north and south instead of northeast, as is that of the later folding in this region.

If the beds are returned to a vertical position, it becomes apparent that the present under side was the western side of this series after the first folding. As we have seen, this represents the upper sides of the strata, and it thus becomes evident that we are dealing here with the western limb of an anticline of the first period of folding. Since the western limb was vertical, the eastern one must have had a gentler dip unless the folds were isoclinal. Observation of other sections in this region confirms the supposition of an asymmetric anticline, which thus appears to represent folding in the same general direction, *i.e.* toward the west, as was that of the later foldings. These conditions before the second folding are restored in the section (Fig. 528 *b*), which covers a larger field than is shown in the preceding figure.

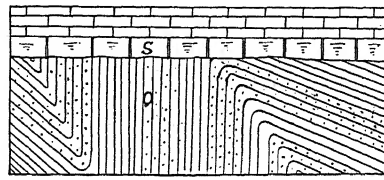


Fig. 528 *b*.—Relation of the Ordovician sandstones and Silurian limestones of the Vlightberg region at Kingston, N. Y., before the last folding.

It is by such analysis of the facts, and reasonings therefrom, that the geologist is enabled to reconstruct the conditions which existed at a given period in the earth's history at the locality under observation, and from many such observations over wide areas he is enabled, by combinations, to write a moderately complete chapter of the history of his country at a given period in the far distant past.

Structures Due to Folding, Erosion, and Renewal of Deposition

Unconformities and Disconformities

Unconformities. — In the example of complex structure described in the last section (Fig. 528 *b*), we have seen that horizontal beds (*S*) are deposited upon the eroded edges of an older folded series. The two series of beds thus have a discordant relation, their dips being in different directions and of different degrees, in one part at right angles to each other. Such a relationship is termed an *unconformity*, a term sometimes qualified by prefixing the word

angular. When such an unconformity exists, it always points to the folding and erosion of the older series before the deposition of the younger, which rests unconformably upon the older. Such

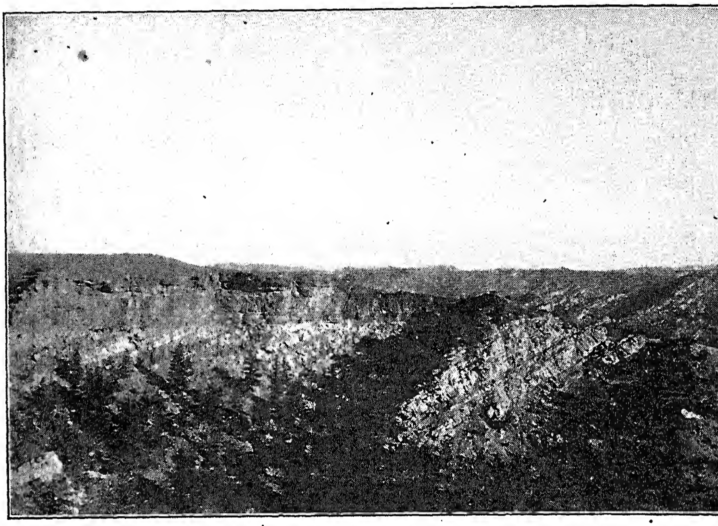


FIG. 529. — Typical unconformity between inclined sandstones ("Laramie") below (dipping to the left) and horizontal conglomerates (Basal Wasatch) above. Near Meeteetsie, Wyo. (Photo: C. A. Fisher, from U. S. G. S.)

a relation implies the existence of a time-interval between the deposition of the two series, during which the folding of the older series and its partial erosion took place. In the example cited, where the older beds are of Middle Ordovician age and the younger of Upper Silurian, the interval comprises the Upper Ordovician and the Lower and Middle Silurian eras. It is probable that the folding of the older series occurred in Upper Ordovician time, which would leave the Lower and Middle Silurian periods for the accomplishment of the erosion.

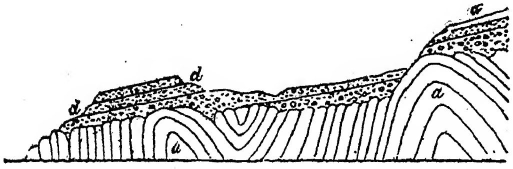


FIG. 530. — Unconformity at Siccar Point, Berwick, Scotland. *a*, folded and truncated Siluro-Ordovician beds; *d*, Old Red Sandstone beds (Devonian). (After Lyell.) See Figs. 531 *a*, *b*.

Unconformities are met with in all geological formations in regions where folding of strata has occurred. Sometimes the later series has not been folded and then it represents horizontal, or nearly hori-

FIG. 531 *a*. — Irregular, unconformable contact between the vertical (on right) or steeply inclined (on left) Siluro-Ordovician shales, and the gently dipping Old Red Sandstone beds in the center and foreground. Note that the older beds often project into the basal beds of the Old Red series, which were deposited in the hollows between. The higher Old Red beds have been removed by subsequent erosion. (Photo, M. I. Goldman.)

zontal, strata resting abruptly upon inclined beds (Fig. 529). This is well shown in the unconformity between the Siluro-Ordovician beds and the Old Red Sandstone at Siccar Point, near St. Abb's Head (Berwick), Scotland (Figs. 530–531 *b*), and at Banff on the

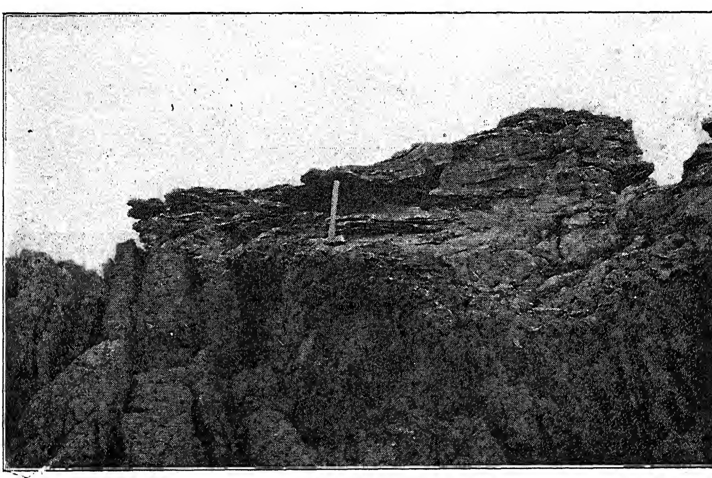


FIG. 531 *b*. — Near view of the unconformity at Siccar Point, Scotland, showing horizontal basal Old Red conglomerates resting on vertical Siluro-Ordovician shales and sandstones. (Photo, M. I. Goldman.)

south shore of the Moray Firth (Fig. 532). Other illustrations of unconformities will be cited in the chapters on Historical Geology.

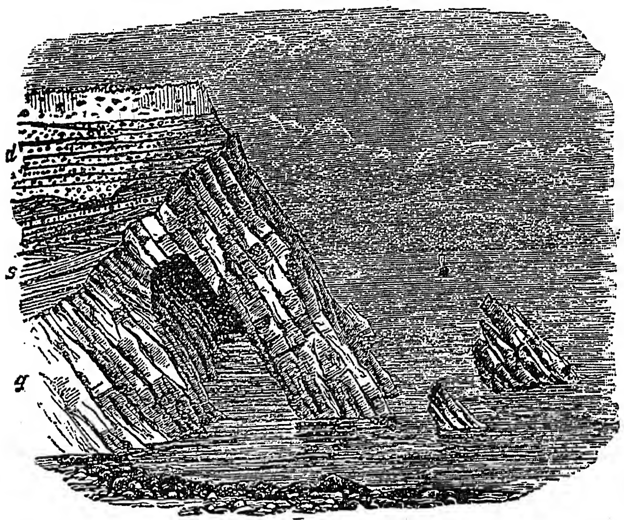


FIG. 532. — Unconformity and disconformity exposed on the coast of Banffshire, south shore of Moray Firth, Scotland. *q*, quartzite (Siluro-Ordovician); *s*, Old Red Sandstone; *d*, drift resting disconformably upon the Old Red beds, and unconformably against the older series. (After Geikie.)

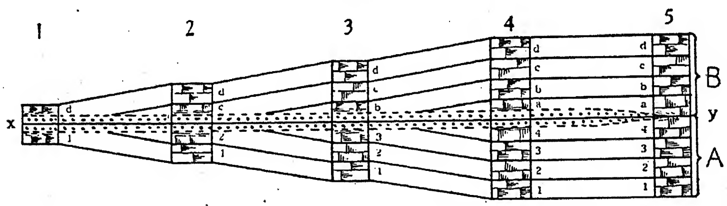


FIG. 533. — Diagram showing the relationship of the strata in five successive sections, in a compound regressive-transgressive series. The intercalated sandstone *xy* encloses the hiatus. (From *Principles of Stratigraphy.*)

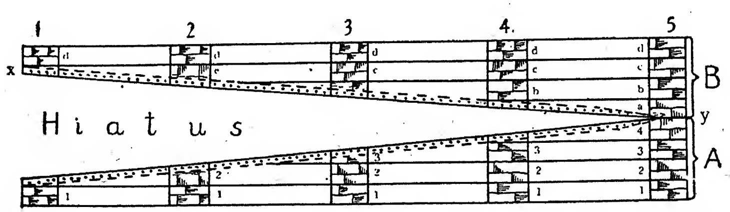


FIG. 534. — Diagram showing the relative magnitude of the hiatus in the various sections shown in Fig. 533. (From *Principles of Stratigraphy.*)

Disconformities. — Where the surface of a low dome, such as that of the Cincinnati dome, or the margins of a shallow basin, such

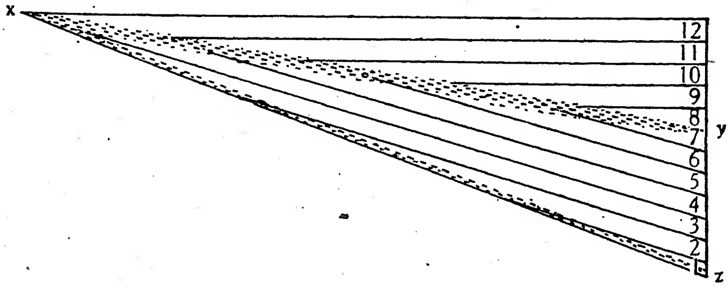


FIG. 535. — Diagram showing the relationships of a transgressive-regressive-transgressive series. A hiatus is found at the base of the transgressive series (*xz*) and between the regressive and upper transgressive series (*xy*). Owing to the vertical exaggeration of the scale the essential parallelism of the strata is not expressed. (From *Principles of Stratigraphy*.)

as the Michigan basin, are eroded and later strata deposited upon the eroded surfaces, the difference in the dip of these two series will be so slight that it cannot be measured, much less seen by the

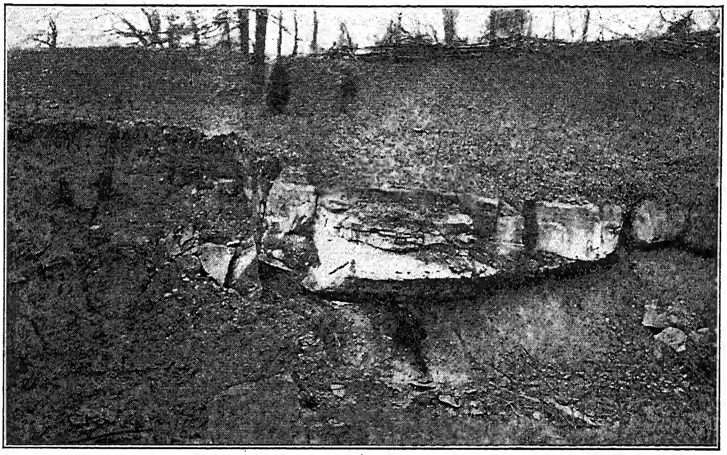


FIG. 536. — Disconformable contact between the Bedford shales below and the Berea sandstone above, the latter resting in erosion hollows in the former. Near Cleveland, O. (C. S. Prosser, photo.)

eye. Nevertheless, there may be a pronounced break in continuity between the two *apparently concordant* series, and this break may represent a long time interval. A similar break in continuity may

be produced when a series of strata left exposed on the retreat of the sea, after a long time interval is again covered by the advancing sea in which strata of much younger age are deposited in the manner illustrated in the preceding diagrams (Figs. 533–535). When such a break in continuity is established between two successive formations which have a parallel or concordant position, it is designated a *disconformity*. The break and disconformity may be indicated in many ways. The older series may show evidence of erosion on its upper surface (Fig. 536); pebbles of the older series may be included in the base of the upper one; an old soil bed, or a bed of eolian sands, may separate two marine formations (Fig. 535), this bed indicating an emergence followed by a submergence. Sometimes, however, no such detailed characters are shown, and then the disconformity and break are indicated only by the great difference in age of the two formations and the absence of an intermediate series that should intervene (Fig. 537). This difference in age is shown primarily by the fossils which the rocks contain and by the known succession of the series elsewhere. In some cases the line of disconformity is marked by springs (Fig. 538). In Fig. 532, a section is given showing both unconformity and disconformity.

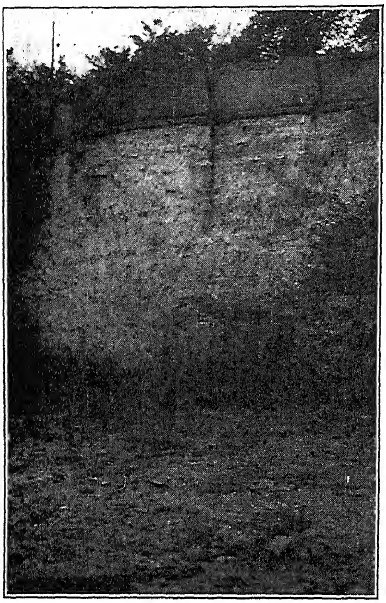


Fig. 537. — Disconformable contact between the Cobleskill limestone (Upper Silurian) above, and the Brayman shales (Middle Ordovician) below. Near Howe's Cave, N. Y. (C. C. Mook, photo.)

Diastems. — This term has been applied to minor breaks in the continuity of a series of strata due to a temporary cessation in sedimentation followed by its resumption at a later period, but as a rule without erosion or even emergence of the older strata (if they are marine), as is always the case in a disconformity (Barrell).

FIG. 538. — Disconformable contact between the Akron dolomite (Upper Silurian) and the Onondaga limestone (Middle Devonian), at Williamsville, N. Y. The contact is marked by the line of springs. (Photo by author.)

THE CAUSES OF FOLDING

Folding of the rocks of the earth's crust always implies compression, and in a folded region the crust has become correspondingly shortened. The monoclinal flexure must, however, be excepted,

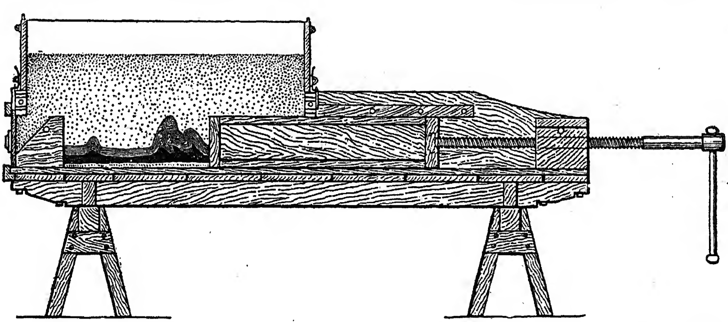


FIG. 539. — Machine for producing folded strata. Baily Willis. (From Martonne, *Géographie Physique.*)

for this is not necessarily due to compression. That folds are produced by lateral compression of horizontal layers of material can easily be shown by experiment. It is only necessary to press the

leaves of a book against the back of the cover to produce folds in the paper. More elaborate experiments with layers of wax and other substances to represent the strata have been made in a machine permitting slow and regular compression. In such an experiment the strata to be folded are generally weighted by a load of shot, on the supposition that folding is best accomplished in nature beneath a load of surface rock material, and that in the absence of such a load the layers will fracture and become dislocated. A machine of this type is illustrated in figure 539, and by its use many of the characteristic types of foldings found in the strata of mountain regions have been reproduced (Fig. 540).

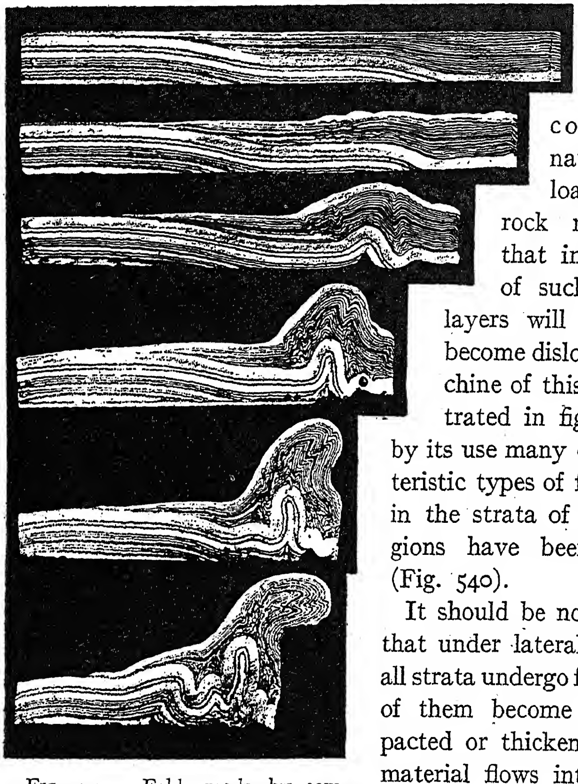


Fig. 540. — Folds made by compression of layers of wax and other substances in the machine illustrated in Fig. 539. (U. S. G. S.)

It should be noted, however, that under lateral pressure not all strata undergo folding. Some of them become merely compacted or thickened, and their material flows into any spaces released under the pressure. Such strata, among which clay rocks are found, have been called "incompetent beds" in contradistinction to the "competent beds," which are thrown into folds by the compression. In many cases thrust faulting accompanies folding, the one passing into the other (Fig. 541).

In the folding of the Appalachian Mountains, the crust of the earth has been shortened to an amount estimated at from 40 to 50 miles and in some portions probably more. In the Swiss Alps

the foreshortening was originally estimated at 74 miles, but more recent studies have led to the conclusion that the original Alpine geosyncline was from 400 to 750 miles broad, and that it has been reduced by folding and mashing to 100 miles. In the

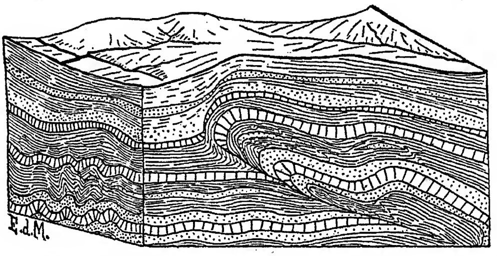


FIG. 541.—Diagram showing passage of thrust fault into fold. (After de Martonne.)

Rocky Mountains of British Columbia an area originally 50 miles wide has been reduced to a width of 25 miles by such compression.

There are a number of theories which aim to explain the causes of the compressive movement. Among these the one held longest, appeals to the gradual shrinking of the earth's interior through loss of heat, and the inward pressure of the cool crust, with the result that tangential strains are set up within this crust. Other causes appealed to are: the transference of subcrustal molten material to the surface; isostatic readjustment; escape of volatile substances; changes in the oblateness of the spheroid toward a more spherical form; migration of the equatorial bulge with change in polar position, etc. The subject is too complex for elementary treatment, nor are all of the elements of the problem as yet fully understood.

DEFORMATION BY FAULTING

Definition of Terms

A fault is a displacement of the strata of the earth's crust on opposite sides of a fracture plane or surface. Faults affect all kinds of rocks, but are most readily recognized in the stratified deposits, and the illustrations will therefore be taken from them. The surface along which the movement has taken place is called the *fault-plane*, or better, *fault surface*, as it is not a perfect plane except for short distances, but curved, warped, irregularly broken, and even with offsets. Sometimes there are a number of more or less parallel surfaces along each of which a small amount of slipping has taken place. In such cases the entire series is re-

ferred to as the *fault zone*, and the displacement itself is called a *step-fault* (Fig. 542).

Owing to the friction along the fault surfaces by the movement against each other of the rock masses, these surfaces are often polished and striated in the direction of movement. Such surfaces are said to be *slickensided*. The line of intersection of the fault surface with a horizontal surface is the *fault-line* (Fig. 543, *F. L.*), and its direction is called its *trend*. (Strike is also used, but this is properly restricted to the intersection of the strata with the surface.) The normal position of a fault plane or surface is assumed to be vertical, and this is called its *zero* (Fig. 543, F_1).

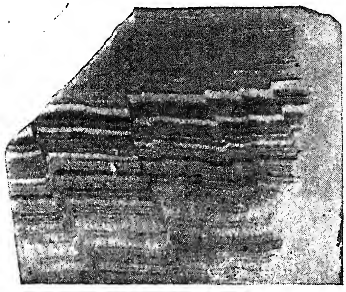


FIG. 542. — Transverse section of a piece of banded sandstone, showing series of small faults. (Photo, B. Hubbard.)

Any departure from this (F_2) is measured with reference to a vertical plane passed through the fault line and is called the *hade* (Fig. 543, $F_2\,h$). It will be seen that this is the complement of the dip, which is the departure from the horizontal, but the term dip should be restricted to the inclination of strata. The dip of the fault plane may be measured with the clinometer and the amount sub-

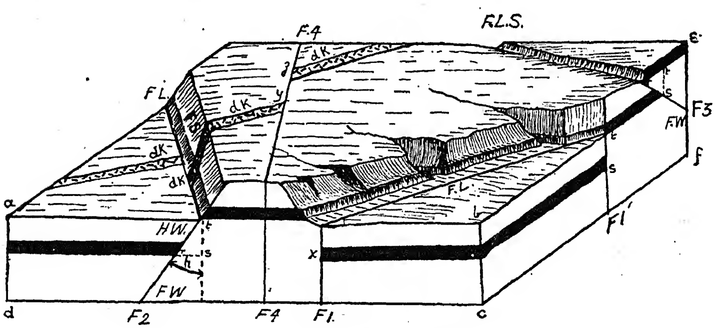


FIG. 543. — Diagram illustrating various types of fault. *F. L.*, fault-line; F_1, F_1', normal fault with vertical fault plane, the fault scarp or cliff has been worn back from the fault-line; F_2, normal fault with inclined fault plane, with hade *h*; *F. W.*, foot wall; *H. W.*, hanging wall; *dk*, dike showing offset because of inclination; *F. S.*, fault scarp, uneroded; F_3, thrust fault; *F. L. S.*, fault-line scarp formed by erosion; F_4, fault without vertical but with horizontal displacement or *shove* as shown by offset in dike (*dk*) at *yz*.

tracted from 90°, the difference being the angle of hade. With an inclined fault-plane or surface the side projecting below is called the *foot wall* (Fig. 543, *F. W.*), while the overhanging side is called the *hanging wall* (Fig. 543, *H. W.*). In a vertical fault plane neither is present. Most faults are best shown in vertical sections.

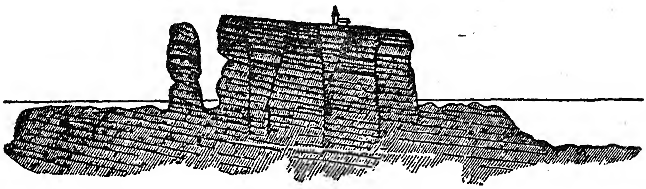


FIG. 544. — Section of the Island of Helgoland in the North Sea, showing numerous faults in the inclined strata, and the decrease in the size of the island, and formation of a submarine platform, by wave-erosion. (After Walther.)

The vertical cliff section of the island of Helgoland cut by the waves of the North Sea shows a number of faults not otherwise noticeable (Fig. 544).

Types of Faults

Nature of Movement in Faulting. — The movement of the two sides of a broken mass in faulting is relative. Both may undergo a change in position of the same or of different extent, or either may remain stationary while the other moves. In any case a displacement results, which is all that is visible of the fault. This displacement is best measured by the change in position of the two parts of a definite, recognizable stratum, such as a coal bed, a limestone layer, or some other bed (x, Fig. 543), which can be recognized by its lithic character and thickness. The movement may be vertical, horizontal, or oblique, or it may be a rotary one, the displacement being of a corresponding character. Only the simpler types will be considered.

Normal Faults. — If the displacement or slipping along the fault plane is in a direction at right angles to the fault line, two distinct cases may be recognized, the normal and the reverse fault. With reference to an assumed stationary footwall, the hanging wall may slip down, thus producing a *normal fault*. This is best recognized upon a vertical face cut at right angles to the fault line (*abcd*, Fig. 543), where it will be seen that the guide or index stratum has been vertically displaced (Fig. 543, F_1, F_2,). The extent of vertical dis-

placement is called the *throw*, this, in F_2, Fig. 543, being measured by the vertical distance $s–t$. There is, however, also a horizontal displacement at right angles to the fault line, and this is called the *heave*. In the present case this is a separation or positive displacement of the beds, and its amount is measured by the distance $r–s$. It is evident that in this case there has been a lengthening of the earth's crust by the amount of the heave, and this implies a stretching movement such as may exist at the top of an anticlinal arch. If the fault plane is vertical the heave is zero. (Fig. 543, F_1'.) Normal faults may also develop upon a monoclinal flexure, where the upflexed side becomes the downthrow side, and the downflexed, the upthrow side. (See p. 602.)

Reverse Faults. — If the hanging wall moves upward with reference to an assumed stationary footwall, the movement again being only in a direction at right angles to the fault line, a *reverse fault* is produced (Fig. 543, F_3). Here, too, we meet with a throw, but in the opposite direction, and if the fault plane is inclined, with a heave which is also in the opposite direction, the result being an overlapping or negative displacement. Here again the amount of throw is measured by the vertical line $s–t$, and the amount of heave by the horizontal line $t–r$, as seen in a vertical section at right angles to the fault plane (*bcfe*). It is clear that in this case there has been a shortening of the earth's crust by the amount of the heave, which would imply lateral compression of the type which produces folded structures.

Surface Expression of Normal and Reverse Faults. — Both normal and reverse faults would be characterized by a cliff or initial *fault scarp* upon the surface immediately after faulting has taken place, if this were more rapid than the erosion which would tend to level the inequalities (Fig. 543, *F. S.*). Fault scarps of this type are sometimes seen in the modern topography where faulting has been so rapid as to be accompanied by an earthquake (Fig. 582, p. 677). Such scarps and the modifications which they undergo by erosion will be considered fully in the chapter on surface sculpture (Chapter XXIII). Two examples, an eroded fault scarp (of F_1) and the revived fault-line scarp *F. L. S.*, are indicated in the diagram (Fig. 543). In normal faulting the initial fault scarp is formed by the footwall, in reverse faulting by the hanging wall.

Horizontal, Oblique and Rotary Faults. — Instead of vertical movements up or down the fault plane, the movement may be con-

ceived as merely a horizontal one along the fault plane, though this is probably rare. Such a fault would produce no initial fault scarp, though a secondary one might be developed later by erosion. The extent of horizontal displacement along the fault plane is called the *shove*, and if the fault plane cuts across strata or across a dike, vein, pebble, or other guiding structure, the amount of the shove along the fault plane can be measured (*yz* in F_4, Fig. 543). An apparent horizontal displacement of the dike is produced by a simple vertical fault, because of the inclination of the dike (Fig. 543, *dk* at F_2).

Probably most faultings involve a more or less oblique movement down or up the fault plane, comprising at the same time lateral displacement along that plane, or the movement may be a double one, partly up or down the plane and partly parallel to it, or it may be rotary, one block being twisted with reference to the other. In any case the total amount of displacement between any two points, originally in contact, can be measured by a direct but oblique line, and this is called the *slip* of the fault. It may be resolved into the three components, the *throw*, the *heave*, and the *shove*, from which measurable units the amount of slip may be calculated. If the fault plane is vertical there is no heave, but the line of slip forms the hypotenuse of a right-angled triangle, the other sides of which represent the throw and shove, respectively. Rotary faults may sometimes be recognized by the difference in dip or strike of the strata on opposite sides of the fault plane.

Strike Faults. — Faults in tilted stratified rocks may have their trend essentially parallel to the strike of these rocks. Such a fault is called a *strike fault*, and it may be either normal or reverse, and the inclination of the fault plane may coincide with the dip of the strata, or may have any angle with reference to it. This is the common type of fault found in folded beds where, moreover, faulting is commonly reverse. Whenever the angle of inclination of the fault plane and the dip of the strata differ in a strike fault, there will be either a concealment or a duplication of the beds in the surface exposures as the result of faulting. The following diagrams (Fig. 545) illustrate these results with varying angles of inclination of the fault plane and constant dip of strata, both in normal faults (*A* to *G*) and in reverse faults (*H* to *J*). It will be seen that in figures *A*, *F*, *I*, and *J* certain beds are concealed at the surface, while in figures *B*, *C*, *E*, *G*, and *H* certain beds are repeated.[1]

Dip Faults, Oblique Faults. — When the trend of the fault line is at right angles to the strike of the strata or nearly so, the fault is

[1] See further, A. W. Grabau, *Principles of Stratigraphy*, pp. 817–818.

spoken of as a *dip fault*, while faults whose trend makes an angle of approximately 45° with the strike are called *oblique faults*. Such faults are commonly indicated by an offset or shifting of the strata on either side of the fault line (Fig. 546).

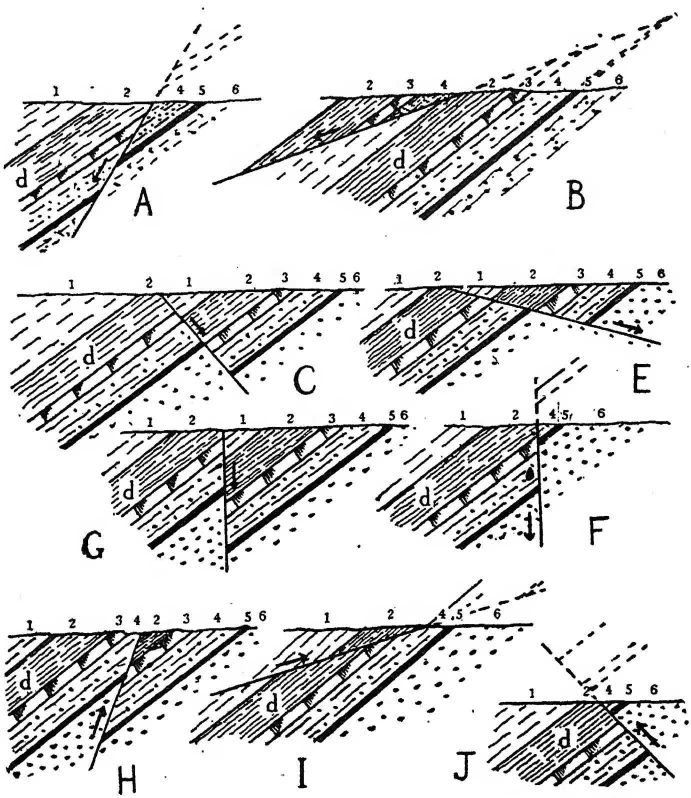


FIG. 545.—Strike faults. *A–F*, Normal or gravity faults, the arrows indicating the downthrow side; *H–J*, thrust faults, the arrows indicating the upthrust side. The diagrams represent the conditions after erosion of the surface. In *A*, *F*, *I*, and *J* certain strata are eliminated, in *B*, *C*, *E*, *G*, and *H* certain strata are repeated. (From *Principles of Stratigraphy*.)

Gravity Faults.—While the terms heretofore used have reference to the nature of the movement (normal, reverse, horizontal, rotary, etc.), or to the relation of the fault and the strata (strike, dip, and oblique faults), there are two other terms in common use which refer to the agent or cause of the movement. These are gravity and thrust faults. The term *gravity fault* implies that one

side slipped down as the result of its own weight, and normal faults are generally assumed to be of such character, the terms being sometimes used interchangeably. A normal fault may, however, be produced by the up-pushing of the footwall, rather than the down-slipping of the hanging wall, as is illustrated by the fault formed during the New Zealand earthquake of 1855 (pp. 675–677, Figs. 581–582).

Thrust Faults. — These, on the other hand, are of common occurrence, and they are generally of the reverse type, but are also much more complicated. They occur on the margins of folded areas and

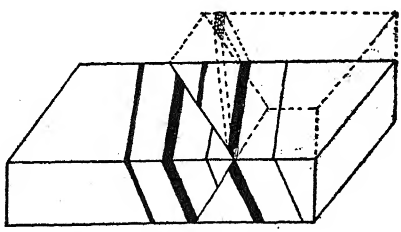


FIG. 546. — Diagram illustrating the offset of strata produced by vertical slipping along an inclined plane, when the fault is oblique with reference to the strata. The dotted outline restores the fault scarp and gives the appearance immediately after faulting, before erosion has removed this portion of the block.

sometimes within them. Indeed, within the same area an overturned fold at one locality may be seen to pass into an overthrust fault in another (Fig. 541, p. 618).

Magnitude of Thrusts. — Thrust faults may range in magnitude from minute slippings of a few feet or less to cases in which the movement has resulted in carrying one rock mass over another for a distance of as much as 70 miles. The most stupendous examples of such thrustings are seen in the Alps, where successive sections have overridden one another, producing a structure of extreme complexity. In the great thrust along the Front Range of the Rocky Mountains in Montana, the observed distance of movement is fifteen miles, while actually it was probably much greater.

Duplication and Inversion of Order of Strata by Thrusting

As the result of great overthrusts, the strata of a given region may be repeated, and because of the nearly horizontal nature of

the thrust the repetition may appear to be perfectly conformable. Unless the thrust is recognized, such a series may be conceived as representing one of unbroken succession. By such thrusting, formations of older may come to rest upon those of younger age, and thus an inversion of the strata may seem to have taken place. Several examples may be cited.

The Helderberg Overthrusts. — In the Helderberg range of mountains, from Catskill southward, a great overthrusting of the strata of Silurian and Devonian age has occurred along the western border of the Appalachian folds, probably for the most part as a

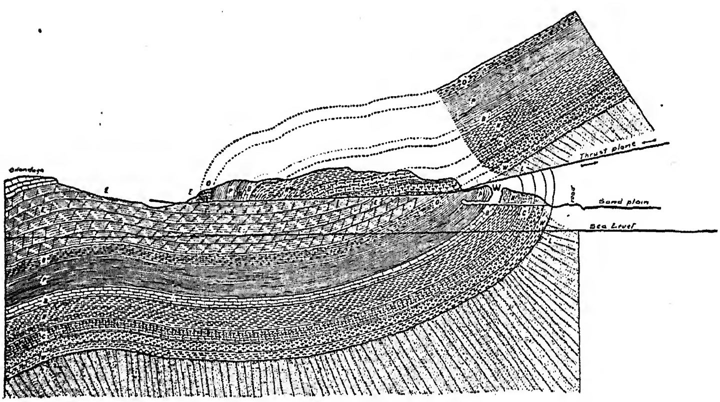


FIG. 547. — Section through North Hill, Kingston, N. Y., showing the overthrust which led to a repetition of the strata. *E*, Esopus shale; *O*, Oriskany sandstone; *P*, Port Ewen; *B*, Becraft; *N*, New Scotland; *C*, Coeymans with Manlius below; *W*, Cobleskill; *Z*, Hudson River strata. (After Van Ingen; N. Y. State Museum Report.)

single overthrust (with perhaps locally a number of parallel slips). By erosion the overthrust mass has been divided into a series of blocks of which the above is an illustration (Fig. 547). In all cases the thrusting is from the southeast, and the entire series of strata from the Upper Silurian to the Middle Devonian is repeated. Before the thrust was recognized it was thought that the beds exposed in those ridges represented a single conformable series in which there occurred a remarkable repetition of similar sediments enclosing similar organic remains.

The Hudson Highlands Thrust (Fig. 548). — The Highlands of the Hudson likewise present a thrust of considerable magnitude, with the result that the older crystalline rocks of the Highlands rest

upon the younger ones, which are exposed farther to the north. This thrusting appears to have been of a compound nature, the

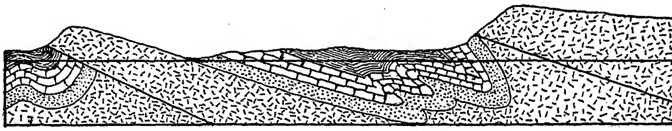


FIG. 548. — Diagrammatic section (generalized), showing the overthrust at the northern end of the Hudson Highlands. *Irregular dashes*, granite, gneiss, and other crystalline rocks of the Highland region; *dotted*, Lower Cambrian (Poughquag) quartzite; *blocked*, Cambro-Ordovician limestones (Wappinger, etc.); *lined*, Hudson River shale — Ordovician. The main overthrust on the right brings the crystalline rocks against the Cambrian quartzite, while the subsidiary thrust brings the crystallines above the Hudson River slates. Thrust movement towards the northwest.

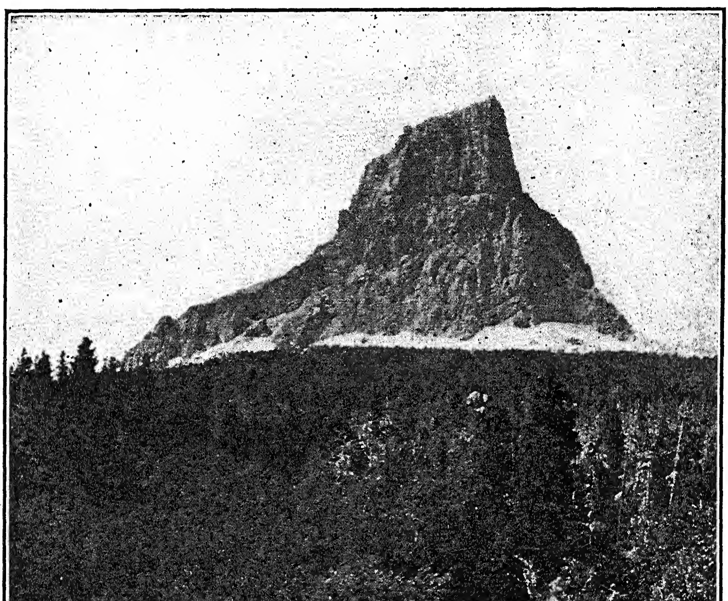


FIG. 549 *a*. — Chief Mountain, Montana. An erosion remnant of a mass of Algonkian limestone carried by thrust faulting over soft sandstones and shales of Mesozoic age, for a distance of at least fifteen miles. The monolith has a height of 1500 feet above the thrust plane, which is indicated in the photograph by the upper line of the forest. (After Campbell, U. S. G. S.) (See Fig. 515, page 599, and Fig. 549 *b*.)

movement occurring along several parallel planes of low inclination. As a result the old crystalline rocks have been repeatedly brought up

to the same level, where subsequent erosion has uncovered them. At several places the old Highland gneisses of Archæan age may be seen to rest upon the upturned Hudson River shales and sandstones of Ordovician age. The movement in this case also was from the southeast to the northwest.

The Chief Mountain Thrust of Montana (Figs. 549 *a*, *b*). — In northern Montana along the Front Range of the Rocky Mountains,

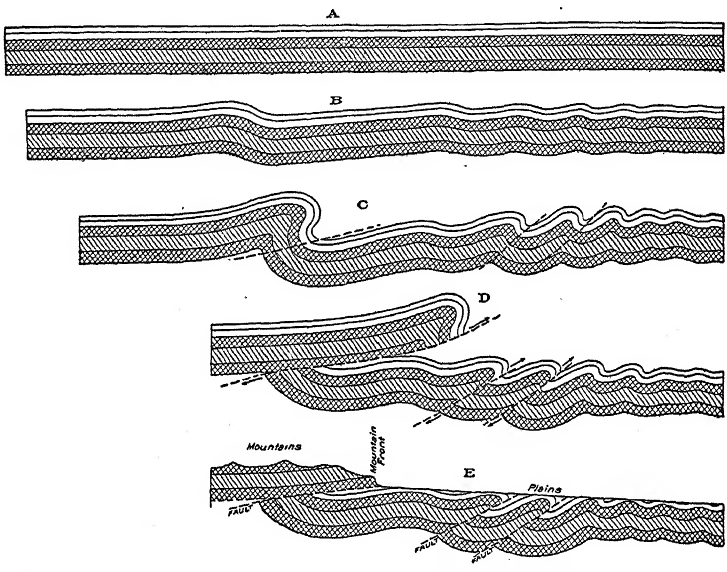


Fig. 549 *b*. — A series of diagrams showing the development of the Chief Mountain thrust. The older rocks from which the mountains are cut are represented by cross-lines, the younger rocks of the plains (Mesozoic) in white. (After Campbell, U. S. G. S.)

strata of Algonkian age are seen to rest with apparent conformity upon nearly horizontal beds of Cretaceous age. These Algonkian masses are erosion remnants of a formerly continuous series, Chief Mountain being the most conspicuous of these remnants. This position of pre-Cambrian upon late Mesozoic rocks at once suggests overthrusting, and an examination of the region to the west shows that this has actually occurred. From the data available the extent of the movement is recognized to have been at least fifteen miles, the direction of movement in this case being eastward. The actual movement was probably much greater, and a considerable portion of the overthrust mass has apparently been

removed by erosion. The development of this thrust-plane is shown in the diagram (Fig. 549 *b*), and the position of Chief Mountain with reference to the other rocks is shown in Fig. 515 on p. 599.

Thrusts in the Northwest Highlands of Scotland. — The northwest region of the Highlands of Scotland shows a wonderful series of thrustings by which the older rocks are repeatedly made to override the younger ones, the ancient gneiss in many places resting upon Cambrian or Ordovician strata. The adjoining illustration shows some of the overthrusts in this region (Fig. 550).

FIG. 550. — Section in the Northwest Highlands of Scotland showing the overthrust of the Archæan (1) onto the older Palæozoics (2–7): 1, Lewisian Gneiss, 2, Torridon sandstone; 3–6, Lower Cambrian, or Eriboll series (3, Basal sandstone and conglomerate, 200 ft.; 4, Pipe rock, quartzite, with worm tubes, 300 ft.; 5, Fucoid shale with *Olenellus*, 40–50 ft.; 6, Serpulite grit); 7, Durness limestone series, Lower Cambrian and Lower Ordovician. (After Scottish Geological Survey.) Length of profile about 11 Km.

The Salt Range District of India. — In northwestern India a series of mountains forming what is known as the Salt Range, because of the abundance of rock-salt in it, illustrates an interesting problem which may arise from great thrustings. The rocks of this region appear to represent a conformable series, with red sandstones, shales, and extensive salt beds at the base, overlain by marine strata with organic remains of Cambrian age. From this relationship it was originally assumed that the great salt beds of the Salt Range were of early Cambrian or of Pre-Cambrian age, constituting thus the oldest salt deposits of the earth. More recent studies, however, have shown that we are dealing here, not with a conformable series, but with an enormous overthrust, which has carried the fossiliferous Cambrian sediments over the much younger salt beds, upon which they have

come to rest in apparently conformable position. The salt beds themselves are probably of Tertiary age.

The Alpine Overthrusts. — By far the most complicated series of overthrusts which have yet been worked out are found in the

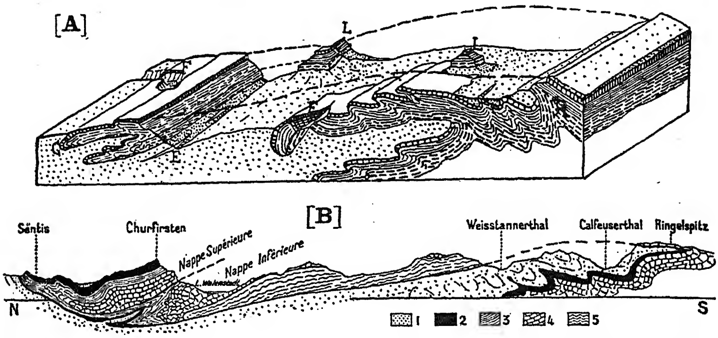


FIG. 551. — Block diagram [*A*] and section [*B*] illustrating overthrust in the Alps. (After Lugeon.)

Alps, where the magnitude of the thrust movement seems at times to be almost incredible. In the preceding illustration some of these great overthrusts are shown (Fig. 551, see also Fig. 524, p. 607).

Topographic Features Due to Faulting

Fault Scarps. — We have already seen that both normal and reverse faults are expressed upon the surface of the earth by fault scarps, if the dislocation is more rapid than the erosion which tends to cut away inequalities (Fig. 543, p. 620). In all but the most recent faults, the scarp is modified by erosion, which may remove it completely or to a position distant from the fault line. Scarps along fault lines may also be resurrected by erosion so that the cliff is not the original fault scarp, but an erosion cliff due to the wearing away of the rocks on one or the other side of the fault line. (See further, Chapter XXIII.)

Rift Valley or Graben. — By the downfaulting of a long series of narrow blocks of the earth's crust or a series of parallel blocks a *rift valley* or *graben* is produced. This is well illustrated by the Graben of the Rhine in the Basel-Strassburg region (Fig. 552), where ancient rocks form the Vosges Mountains and Black Forest on opposite sides, while the center represents a series of much younger strata which originally were, in part at least, continuous with

those now lying on the outer flanks of these mountains, and probably formed an arch with them, the center of which was broken down, as illustrated in the following diagram (Fig. 553).

Other rift valleys are found in eastern Africa (Fig. 554), and of one of these the Dead Sea of Palestine is apparently the northern continuation or a part of a parallel rift which also involves the Vale of Araba and the Gulf of Akaba (see map Fig. 649). On the African Continent these rift valleys have been divided by the building up of volcanic cones at various points, and the resulting divisions of the valleys are partly occupied by lakes, of which Lake Tanganyika is one of the largest.

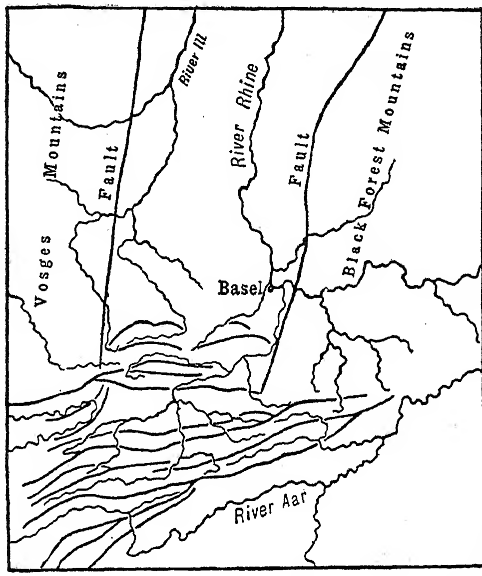


FIG. 552. — Map of rift valley of the Rhine, showing the main faults on either side, and the dying-out folds of the Jura Mountain system on the south where they are crowded against the Vosges and Black Forest massifs. (After Lake and Rastall.)

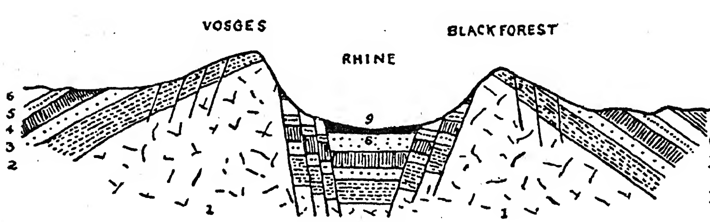


FIG. 553. — Section of the rift valley of the Rhine. 1, granite; 2–7, Mesozoic rocks; 8, 9, Tertiary and recent. (After Lake and Rastall.) For the development of this graben see Fig. 650.

The rift valley in which this lake lies is more complicated in structure than that of the Rhine, consisting of a number of tilted

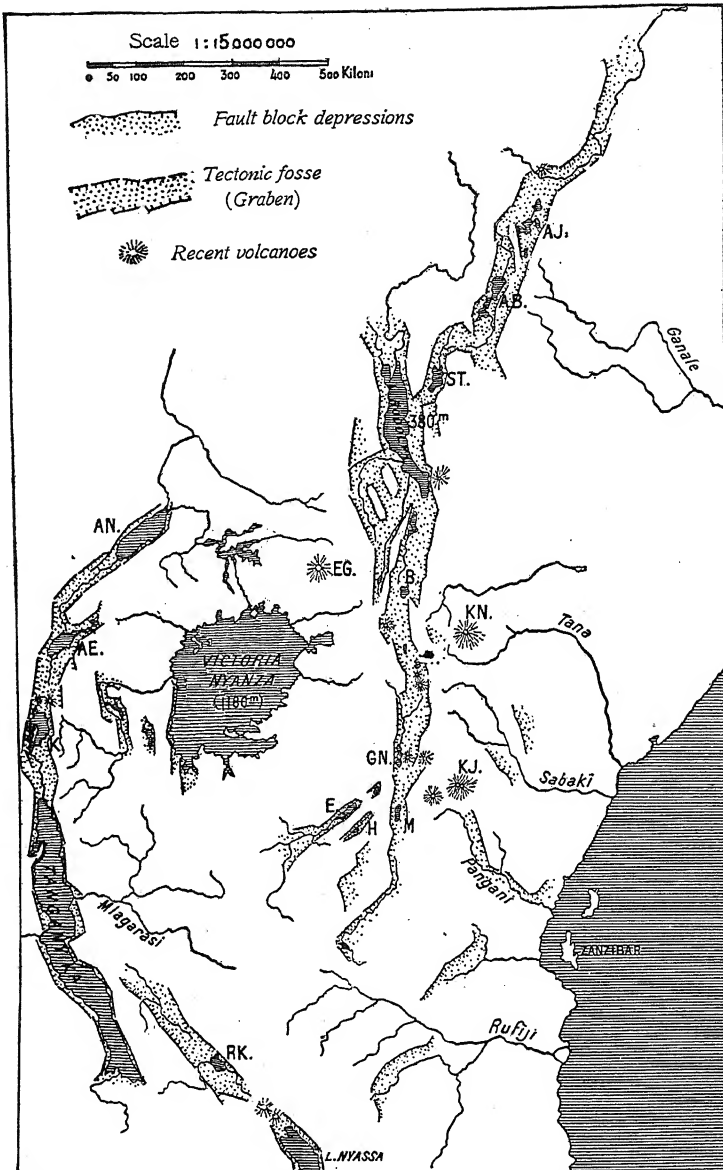


FIG. 554.—Rift valleys of East Africa. After Suess etc. from de Martonne.

AN, Lake Albert; *AE*, L. Albert Edward; *K*, L. Kivu; *RK*, L. Rikwa or Rukwa; *E*, L. Eyassi; *H*, L. Hohenlohe; *M*, L. Manyara; *GN*, L. Guano Nyiro; *KJ*, Mt. Kilimanjaro; *KN*, Mt. Kenia; *N*, L. Naivasha; *EG*, Mt. Elgon; *St.* L. Stefanie; *AB*, L. Abaya; *AJ*, L. Afdjada.

blocks instead of a normal downfaulted mass, as in the latter case. This is shown by the following cross section (Fig. 555).

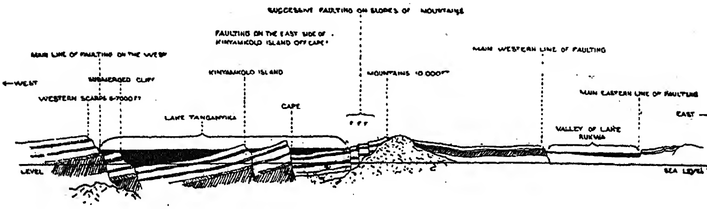


FIG. 555. — Cross-section of Lake Tanganyika and Lake Rukwa, Africa, showing the block and graben faulting. Vertical scale exaggerated five times. (After Moore.)

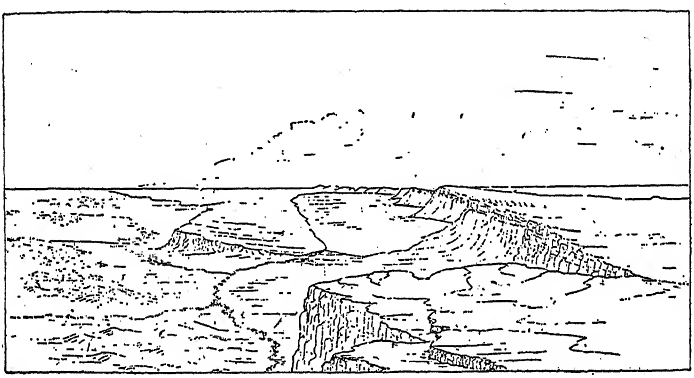


FIG. 556. — Sketch of Lake Albert, Oregon, a fault basin lake. (After Russell.)

A similar valley, with a fault scarp on one side only, is in part occupied by Albert Lake in Oregon (Fig. 556), and there are many other examples of such asymmetric rift valleys, all of which in reality represent block faulting. The rift valley occupied by the Dead Sea of Palestine is of comparatively recent origin, for on opposite sides are still found remnants of beds which were deposited in a lake which once extended across this region before the valley was formed.

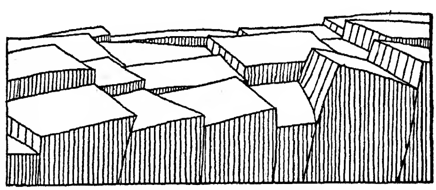


FIG. 557 *a*. — Diagram illustrating block faulting, and the initial stage in the formation of block mountains. See further, Figs. 643, pp. 647 and 648. (After W. M. Davis.)

Block Faulting and Mountains. — When by faulting large blocks of the earth's crust become tilted, they will present a steep fault-scarp on one side and a slope, that of the original surface, on the other. When of sufficient magnitude, such blocks will form moun-

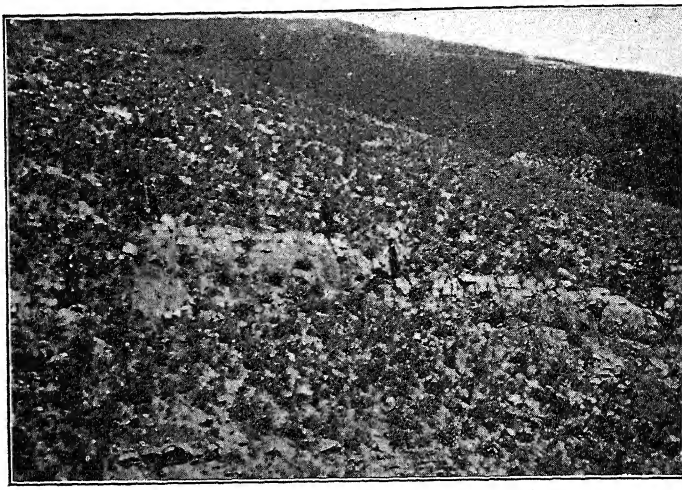


Fig. 557 *b*. — Block faulting with the formation of elevated horsts and depressed rifts. Wasatch Mountains, Utah. Men are standing on the ends of the fault blocks. (Photo F. J. Pack.)

tains. Of this type the Great Basin Ranges of the western United States are the most conspicuous examples (Figs. 557 *a*, 645). An uplifted block, bounded by faults, is called a *horst*. Faulting of this type, but without surface expression, is illustrated in the above view from the Wasatch Mountains (Fig. 557 *b*).

Minor Features Accompanying Faulting

Slickensides. — We have already seen that along the sides of the fault plane, the rocks are often polished and grooved by the movement, producing the characteristic *slickensided* surfaces. Such surfaces are often the best indications of the position of the fault planes, but they are also developed along minor planes of movement parallel to the main fault.

Fault Breccia. — Another feature often produced between fault surfaces, is the complete fracturing and partial powdering of the rocks which form either side of the fault plane. This broken ma-

terial may accumulate in a fissure in the fault and there produce a *fault breccia* (Fig. 32, p. 80). Fault breccias are most conspicuous in normal faults, but they are also found along thrust planes, where they may be so much modified by the movement that the larger fragments lose their angularity and come to resemble a bed of pebbles. The material produced by great ice masses moving over a rock surface is analogous to this, as already outlined in a previous chapter. When a single large mass of rock is caught between two faults it is spoken of as a "horse" (Fig. 558).

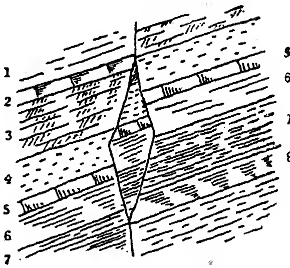


FIG. 558. — A "horse."

Collapse Breccias. — Masses of angular fragments produced by the collapse of the roof of a cave or other hollow, may have a very similar appearance to a fault breccia, but would occupy a more circumscribed area, while at the same time they are apt to be of greater thickness.

Crumplings and Drags. — Minor crumplings of the rocks along the fault plane may also result from the movement, and the angle of the beds on either side of the plane may be modified by a dragging

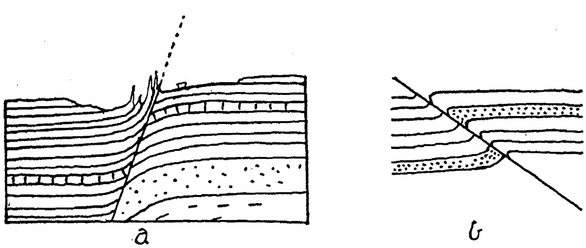


FIG. 559. — Diagrams illustrating drag of strata along a fault plane — *a*, normal fault; *b*, reverse fault. (The reverse bending of the strata near the fault plane is shown in inverted faults formed upon a monoclinal flexure as shown in Fig. 518 *b*, p. 602.)

movement. Thus in a normal fault in horizontal strata, the beds of the hanging wall may be sharply dragged upward along the fault plane while in a reverse fault they may be dragged downward (Fig. 559). The vertical strata from which the Gateway to the Garden of the Gods and the "Cathedral Spires" are cut have been considered as having been dragged to a vertical position along a

fault plane (Figs. 560, 561). Where "inverted" faults are formed upon a monoclinal flexure, the strata near the fault plane bend in

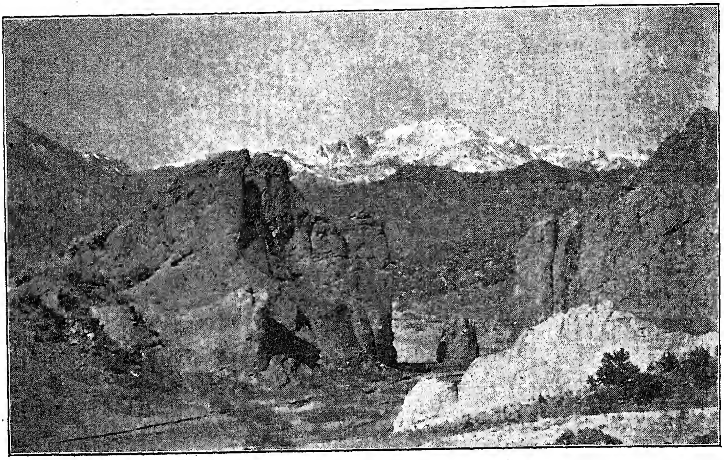


FIG. 560. — Gateway to the Garden of the Gods, Colorado, with Pikes Peak in the distance. The strata which form the "Gateway" are red sandstones apparently dragged to a vertical position by faulting.

the opposite direction, *i.e.* down on the downthrust and up on the upthrust side. (See p. 600, and Fig. 518, p. 602.)

OTHER STRUCTURES PRODUCED BY DEFORMATION

In the deformation of the strata of the earth's crust, structural features of a less conspicuous character than the folds and faults are produced. The metamorphism of the strata due to pressure and the development of heat thereby, and the special structural features of these, will be discussed in the next chapter. Two types of structure, however, may be considered here; namely, *slaty cleavage* and fracture planes or *joints*.

Slaty Cleavage

When the finer-grained rocks are subject to intense squeezing, the particles of such a rock may become flattened and expand at right angles to the compression. This results in a squeezing together of the mass in the direction of compression and a proportional swelling at right angles thereto. If mica scales or other fragments which already have a scaly form are present, they will become so

arranged that their longer axis is at right angles to the direction of compression. In this manner, a secondary parallel structure is produced in the rock thus compressed, this parallel structure being at right angles to the direction of compression, and having no reference to the original structures, such as bedding planes, etc. On weather-

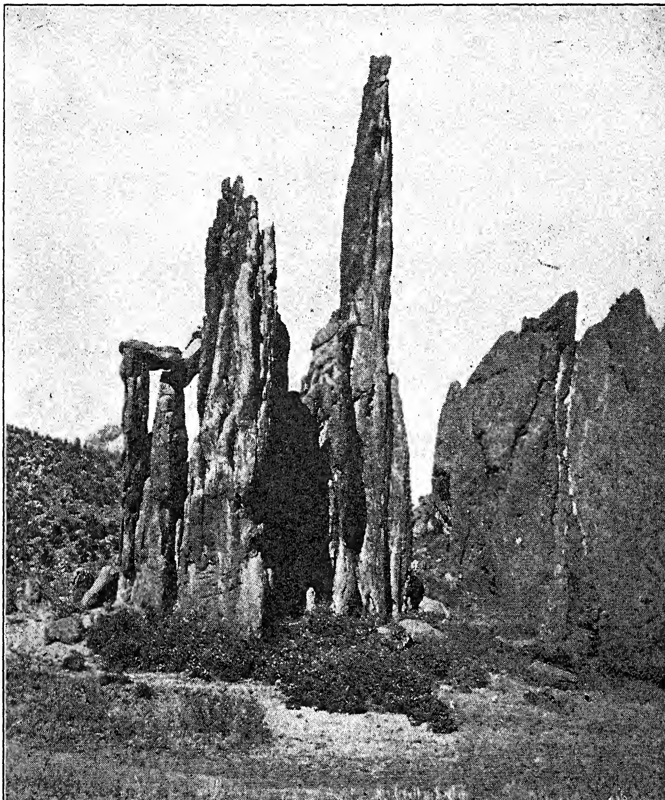


FIG. 561. — The Cathedral Spires, Garden of the Gods, Colorado. These spires are parts of vertical beds of red sandstones, which are modeled out by erosions of the softer beds. (Photo by Darton, U. S. G. S.)

ing, the rock thus affected will split into thin plates along these newly-produced structure planes, or the rock may be artificially split along them. This is called *slaty cleavage*, and it is most commonly developed on clay mud-rocks, such rocks when thus affected producing the common slates used for roofing purposes, etc. (Fig. 562). Slates of this kind may appear banded transversely to

their surfaces, such bands commonly representing the original bedding-planes of the mass before it was affected by the compression. When the original rock contains fossils, these will be compressed and variously distorted, but such rocks are not as a rule capable of furnishing good roofing or other slates.

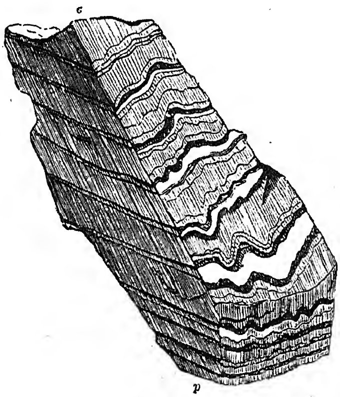


FIG. 562. — A piece of rock in which slaty cleavage has been developed, as shown by the fine lines (p); the coarser bands represent the original bedding planes, now compressed and contorted. (After Le Conte.)

Joints

The term joints and jointing as applied to rocks covers a number of structures, such as the columnar jointing of basalts, the horizontal or arched jointing of granites, etc., and the vertical fissures which are found in nearly all clastic rocks. It is this last type alone which is of deformational origin, though it is not necessarily confined to the clastic rocks, where, however, it is most perfectly developed. As seen in beds of shale, limestones, or fine-grained sandstones, such joints are commonly found arranged in systems, the joints of each system being parallel, while the different systems form angles with one another. In general, there are two such systems present, crossing each other at a high angle and dividing the rock mass perpendicularly to the bedding planes into a series of quadrangular blocks or prisms, which greatly facilitate quarrying

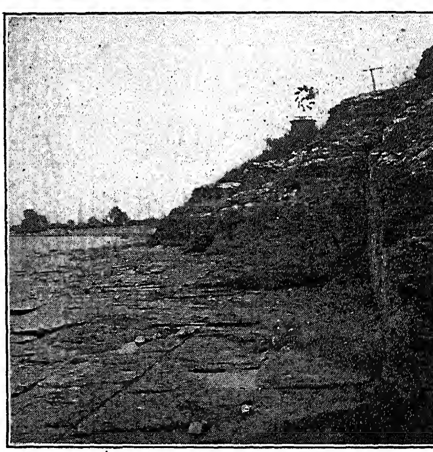


FIG. 563. — Master joints in soft shale (Upper Marcellus) on the shore of Lake Erie. (Photo by author.)

operations and permit weathering and mechanical erosion to produce a variety of forms. In figures 563 to 566 some illustrations of such jointing are given; in soft shales on the shore of Lake Erie (Fig. 563); in sandy shales and sandstones on Cayuga Lake (Fig. 564), and in limestone or chalk where they control the erosion on the coast of France (Figs. 565, 566). (See also Figs. 341 *a*, p. 407, and 474, p. 571.)

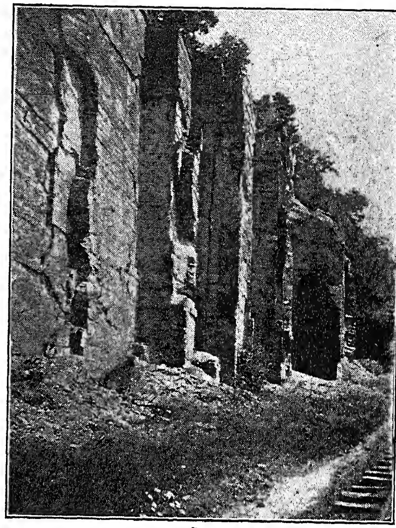


FIG. 564. — Joint planes in Sherburne sandstone, shore of Cayuga Lake, N.Y. Two sets of joints cut the horizontally bedded fine-grained sandstones, and erosion has removed the portion on the right, leaving the huge square prisms of rock facing the lake. (E. M. Kindle, photo; from U. S. G. S.)

Some of these joints extend through the entire mass of the formation, others are limited to a single stratum. The first are called master joints and often exert an important influence on the topography (Figs. 564, 565). The others, the minor joints, are of small significance.

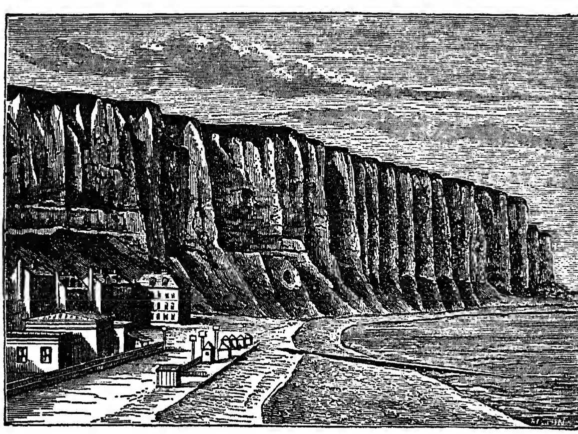


FIG. 565. — Sea cliff 100 meters high at Tréport, France, showing the effect on the coast topography of joints which traverse the beds of chalk in two principal directions. (Copied from Crosby.)

Such joints appear to be the result of the fracturing of strata under a torsional strain. If a great horizontally lying plate of glass were raised by one corner, the weight of the plate would tend to set up sagging or torsional strains and these might be so powerful

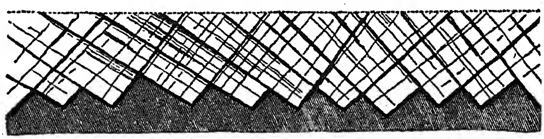


FIG. 566. — Plan of the joints in the chalk cliffs of Tréport, showing how they influence the process of erosion. (Copied from Crosby.)

as to overcome the cohesion of the mass and produce fracture. This can be illustrated by gently twisting a strip of glass held firmly by one end, as illustrated in the annexed figures (Figs. 567 *a*, *b*). When the strain becomes too great, the glass will break,

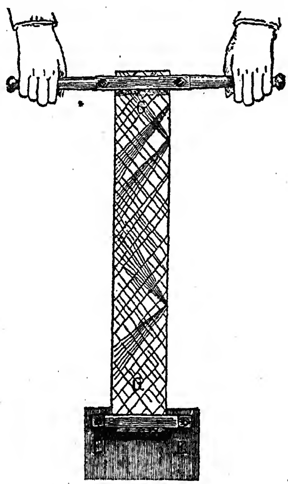


FIG. 567 *a*. — Apparatus for breaking a plate of glass by torsion, with an example of results produced. (After Daubrée.)

with the formation of two or more regular systems of parallel cracks, the cracks of one system crossing those of the other at a high angle. Such cracks reproduce in all essentials the joint cracks formed in stratified rocks.[1] If the twisting is not carried far enough to produce actual shattering of the glass, this can be

[1] In this experiment the glass should be reënforced by a sheet of paper glued to one side which will keep the fragments in place after cracking.

produced by striking a blow with a hammer on the table on which the experiment is made. The shock thus produced will complete the shattering not accomplished by the torsion alone. This illustrates how great sheets of stratified rocks placed under a

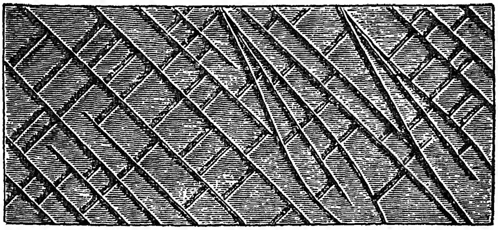


FIG. 567 *b*. — Arrangement of fractures in a large plate of glass which was broken by torsion. (After Daubrée.)

torsional strain by unequal elevation or warping may be shattered by the passage through them of an earthquake shock, and this may be the usual way in which such jointing is produced, as suggested by W. O. Crosby. Joint-like fissures, but of lesser regularity of arrangement, may also be produced in a variety of other ways.

CHAPTER XX

METAMORPHISM AND METAMORPHIC ROCKS

Definition and Classification of Metamorphism

Definition. — All rocks are subject to alteration in nature. This alteration may be slight or intense; it may be accompanied by disturbances in the earth's crust, or it may be the direct result of such disturbances. Changes in the character of the rock are generally recognized by changes in mineral constitution, in texture, or in both, as well as in other characteristics. Such changes are termed *metamorphic*, and the process is one of *metamorphism* (Greek μετά, denoting *interchange* + μορφή, *form*). Some geologists consider all changes as metamorphic changes, but in practice the term metamorphic rocks is generally restricted to those that have been strongly altered, and as a result have taken on a crystalline character.

Classification of Metamorphism according to Forces. — The natural forces producing rock metamorphism are (*a*) chemical energy, (*b*) heat, and (*c*) pressure. All three are commonly active, but one or the other may predominate to such an extent as to give the process its distinctive character. Accordingly we may in a general way classify metamorphism as (1) *chemical* or *diagenetic*, (2) *thermal* and (3) *dynamic*, but it must be clearly understood that these divisions refer only to the dominant force, and that there can be no complete dissociation of any one of them from the others. Chemical energy is indeed active in all processes of metamorphism and may be regarded as the chief of the forces producing changes in rock, but this may be set in motion, or accelerated, by the special intervention of heat, as in the case of a contact with igneous masses or by the influence of great pressure in mountain-making disturbances. It may also act, though slowly, under the ordinary conditions of aging of rocks with time.

Classification of Metamorphism according to Extent. — Metamor-

phism may be *local*, when only a limited area is affected, as in the case of the contact of a rock with a hot igneous mass or with heated waters or gases, or it may be *regional*, when extensive areas are affected, as in the case of great deformation of the earth's crust. Because of the association of regional metamorphism with extensive dynamic disturbances, the two terms, regional and dynamic, are often used interchangeably. It will be well, however, to keep in mind the fact that one term refers to the areal extent of the change and the other to the process producing it. And it must be further understood that in extensive regional metamorphism, deformational changes are not the only causes of alteration, for all other causes, such as invading heat from igneous masses and the passage of gases and liquids which produce chemical changes, may be equally active.

Local metamorphism is most readily seen where heated igneous masses come in contact with other rocks, which they alter, and by which they are altered to a certain extent. This is therefore called *contact metamorphism*, and its characteristics, so far as igneous contacts are concerned, have already been described (p. 207). It should, however, be noted that contact metamorphism is also produced by the passage of heated gases and waters, which generally carry solutions of various substances, and by these the rocks in the neighborhood are affected. Since the chief cause of contact metamorphism is the heat of the igneous body, and since such bodies in contact with other rocks are the chief, though not the only source of heat, the terms contact and thermal metamorphism are often used synonymously. In the following table some of these relations are shown:

Force	*Condition*	*Area*
Chemical or diagenetic.	Static.	Local or regional.
Thermal.	Contactic.	Local.
Dynamic.	Tectonic.	Regional, more rarely local.

Activities of the Agencies Producing Metamorphism

Pressure. — Simple pressure is exerted upon rocks by the weight of other rock masses which overlie them. Such pressure tends to bring closely together the particles of which the rock is composed and may weld them into a more or less solid mass. Certain more plastic layers may also give way at some points and undergo a

flowing movement, with the result that crowding and crumpling of that layer (*enterolithic structure*) (Fig. 568) is produced else-

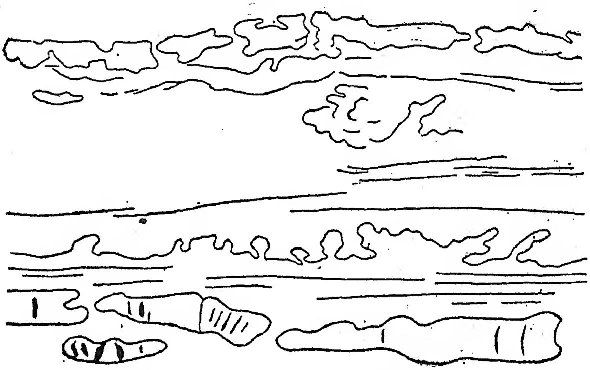


FIG. 568. — Enterolithic structure in fine-grained or compact limestone; Muschelkalk, Neckar Valley, Württemberg. (After Koken.)

where. Pressure and unequal solution along irregular bedding surfaces in massive limestone produces the remarkable structure known as *stylolite* (Figs. 569, 570). Similar deformations are produced in the formation of the great domes of salt which characterize certain districts of the southern United States and of the Old World as well. In these contortion of the salt mass takes place often from the pressure of growing salt crystals, aided in some cases by tectonic forces (Fig. 571).

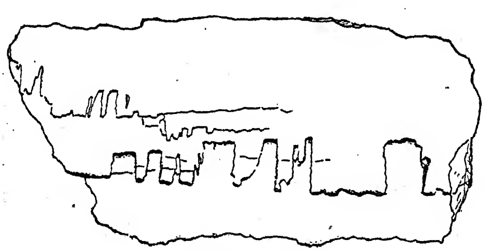


FIG. 569. — Appearance on the transverse face of a limestone layer, showing the formation of stylolitic structure. The interlocking masses have been produced by solution along a minute fracture plane, producing hollows on opposite sides into which the projecting masses fit. The residual clay left on solution is found in both the under and upper hollows and indicated in black. The amount of solution is approximately indicated by the depths of the hollows. (After Wagner.) Greatly reduced.

It is probably also true that rocks under enormous pressure of overlying beds are subject to intense thermal and chemical activities, but of this there is as yet no positive evidence. It has sometimes been assumed that the older rocks of the earth's crust

have become metamorphosed in part because of the great weight of overlying sediments, of which those of the Palæozoic alone, in the Appalachian region, aggregate some 40,000 feet. But it appears that the older metamorphic rocks, wherever they have been exposed by erosion, are overlain by sediments altered but slightly or not at all, and that those rocks were already metamorphosed before these sediments were deposited upon them. Thus the mere pressure of superincumbent rocks seems a minor cause of metamorphism.

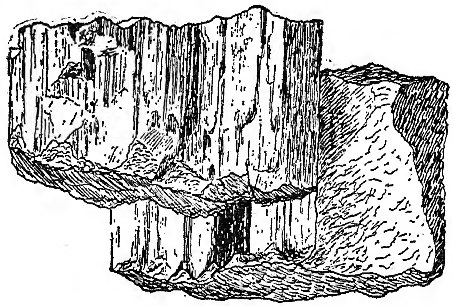


FIG. 570. — Two of the interlocking prisms or stylolites, showing the striated sides produced by friction during the process of interpenetration. About one half natural size. (After Wagner.)

Movement. — The case is otherwise where movement of rock masses has taken place, especially where such movement has been intense and resulted in the production of greatly disturbed structures. Simply folded strata, such as those of the Jura and Appalachian mountains, have been but little affected by the disturbances, and as a rule the amount of metamorphism in them is comparatively slight, though locally it may be of considerable intensity. Where rocks are intensely deformed, metamorphism is generally pronounced.

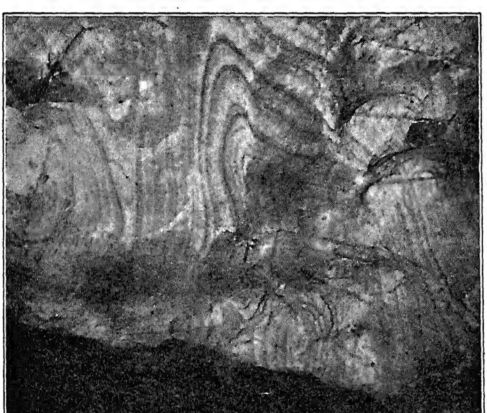


FIG. 571. — Contorted salt layers in the roof of a chamber in Myles Salt Mine, Weeks Island, La. (Photo by Veatch; from U. S. G. S.) These deformations are believed by many to be wholly due to the pressure of growing salt crystals, while others hold that tectonic forces from without aid in their formation, or may even be the chief cause.

Intense deformation is accompanied not only by a change in the form and position of the strata, as in the change from a horizontal to a folded structure, but also by interior readjustment of rock substances, a rearrangement of the rock particles commonly in a parallel manner, together with chemical and mineralogical changes. This is called rock flowage, as distinct from rock fracture, and it is believed to be a process which in most rocks can take place only at a considerable depth, whereas rock fracture is essentially a surface phenomenon. Consequently, the earth's crust is believed to be divisible beneath the belt of weathering into an upper zone of rock fracture (*katamorphism*), and a lower one of rock flowage (*anamorphism*).[1] The limit between the two is at the level where pressure is so great as to close all fractures which may result from movements. It must, however, be emphasized that the depth at which rocks flow rather than fracture depends upon many things, chief among them being perhaps, the nature of the rock. Some rocks, like shales, undergo a flowage comparatively close to the surface, while rigid rocks, like quartzites, may still fracture at a considerable depth beneath it. Therefore if we speak of zones of flowage and fracture, we refer to conditions rather than to actual depth. Nevertheless, at great depths probably no fracturing takes place, all rocks undergoing flowage. Therefore it may be better to speak of the upper portion of the earth's crust as the zone of combined fracture and flowage (according to the nature of the rock), and the lower part as the zone of flowage only.

Heat. — Heat not only affects the mineral particles of the rocks which it invades, but also aids greatly in making the rock undergo flowage rather than fracture. Thus where a rock under pressure is invaded by heat from an igneous mass, flowage may occur much nearer the surface than is the case for the same rock unaffected by the heat. Heat also greatly increases the activity of liquids and gases which enter the rock masses. While heat may be produced in various ways, as by pressure, movements, etc., its most frequent source is probably found in intruded igneous masses.

Liquids and Gases. — These are important agents in producing rock metamorphism. Water is, of course, the most important of the

[1] Leith and Mead ("Metamorphic Geology"), use *katamorphic* for destructive alterations, including weathering, and *anamorphic* for constructive alterations.

liquids. Combined with heat and pressure it becomes a powerful solvent agent and aids in the crystallization of the minerals. Gases arising from an intruded igneous magma are also very active in altering the minerals of the affected rock and in introducing new ones. These agencies appear to be most effective in contact metamorphism.

Metamorphic Structures and Textures

The more important structures produced by metamorphism in rocks are: (1) *cleavage*, (2) *schistosity*, (3) *gneissic structure* and *banding*. The chief texture of metamorphic rocks is crystalline.

Slaty Cleavage. — This has already been discussed in connection with structures produced by deformation (p. 636).

Schistosity. — This structure represents a further development of cleavage in rocks which are subject to intense deformation, with the development of a crystalline texture. The crystals in this case are elongated and have a more or less parallel arrangement not only of form but of mineral cleavage as well. As a result, schistose rocks split readily along the planes of schistosity, sometimes separating between the mineral partings, but more generally along the cleavage planes of these minerals. This is especially the case where mica and hornblende abound, whereas if they are less common than quartz and feldspar, the splitting is mostly between these mineral particles. As a rule the mica and hornblende are new to the schist, having been developed there during the process of metamorphism by recrystallization of substances already in the rock mass.

Fig. 572 *a*. — Banded and contorted gneiss, Fordham, N. Y. (B. Hubbard, photo.)

Gneissic Structure. — "Gneissic structure means a banding of constituents of which feldspar is important, with or without the parallel dimensional arrangement necessary for rock cleavage" (Leith) (Figs. 572 *a*, *b*). Cleavage is not necessarily, nor commonly, very well developed in gneissic structure, but the parallel banding is always marked. "The essential mineralogical difference between gneisses and schist is the possession by the

gneisses of a relatively small amount of the platy and columnar minerals so necessary for a good rock cleavage, and correspondingly more feldspar and quartz" (Leith).

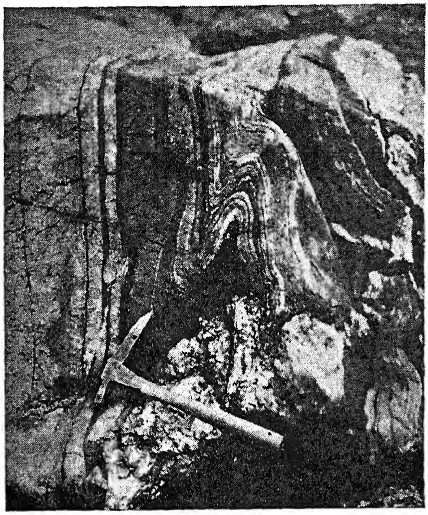


FIG. 572 *b.* — Banded and folded gneiss, Utah. (Photo, by F. J. Pack.)

Crystalline Texture. — This may or may not be accompanied by the formation of schistose or gneissic structure in rock flowage. Marble is one of the best examples in which recrystallization of the carbonate of lime may take place without the formation of a flow structure or cleavage. Recrystallization tends toward an enlargement of the rock particles, and as a result, the original texture of the rock is destroyed (Fig. 573). If the original limestone was of homogeneous character, the bedding planes also are obliterated, but if there were layers differing in character and composition, these are affected in a separate manner, and the bedding structure of the marble or other highly crystalline rock will be retained.

Occurrence and Age of Metamorphic Rocks

Metamorphic rocks are widespread over the earth's surface. Vast areas, such as those of the Canadian Shield, and the greater part of Scandinavia and Finland, show chiefly metamorphic rocks. These are among the oldest rocks of the earth's crust, and it will generally be found that the later rocks (Palæozoic and younger) rest upon them with a very pronounced unconformity, indicating a long time interval between the formation of the two series and a pronounced erosion of the metamorphic rocks before the deposition of the overlying formations.

Highly metamorphosed rocks also occur in the axes of many mountain ranges, where they have become exposed as the result

of erosion of the younger rocks. They in some cases also belong to the older rock series of the earth, but in others are metamorphosed sediments of quite recent date. Thus in the Alps and in the Coast Ranges of Western America, rocks of Mesozoic age have been

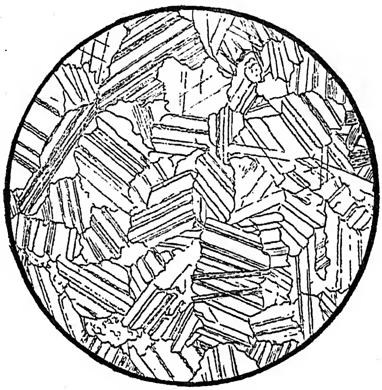


Fig. 573. — Granular crystallized limestone (marble) seen under crossed nicols; enlarged 24 diameters. Fichtelgebirge. (After Rosenbusch.)

highly metamorphosed, and rocks of Tertiary age have suffered a similar change in some parts of the world. In general, however, we may say that the bulk of metamorphic rocks belongs to the oldest geological divisions, being for the most part of pre-Palæozoic age.

Types of Metamorphic Rocks

For the sake of convenience, we shall group the more important metamorphic rocks under the following divisions, which in a general way lead from the less metamorphosed, *i.e.*, those whose original character can still be determined, to the strongly metamorphosed types.

1. Quartzites, slates and phyllites.
2. Crystalline schists.
3. Gneisses.
4. Marbles, crystalline dolomites, ophicalcites, etc.
5. Serpentines, magnetitic and graphitic rocks, etc.

In general, it is easier to predict the types of metamorphic rocks derivable from the common unaltered rocks than to state positively what was the original condition of a given metamorphic rock. In the following table, the more usual metamorphic derivatives of the common rocks are given.

METAMORPHIC DERIVATIVES OF COMMON ROCKS

ORIGINAL ROCK	METAMORPHIC DERIVATIVES
1. *Igneous or Pyrogenic Rocks*	
a. Coarse-grained acid feldspathic types, such as granites, syenites, etc.	*a.* Gneiss
b. Fine-grained acid feldspathic types, felsites, etc.	*b.* Phyllites and schists
c. Coarse-grained basic types	*c.* Basic gneiss; serpentine
d. Finer-grained basic types rich in ferro-magnesian minerals (basalts, dolerites, etc.)	*d.* Hornblende schists and other basic schists
2. *Aqueous (Hydrogenic) and Organic (Biogenic) Rocks*	
e. Precipitated and organic limestones	*e.* Marbles
3. *Clastic Rocks*	
f. Conglomerates and breccias (rudytes)	*f.* Gneisses; schists
g. Sandstones (arenytes)	*g.* Quartzite; quartz mica schist, etc.
h. Clay and quartz flour, *i.e.*, mud-rocks (lutytes)	*h.* Porcelanites, argillites and hornfels; slates; phyllites; mica schists
i. Clastic limestones	*i.* Marbles; calcareous schists
j. Pyroclastic rocks (tuffs, etc.)	*j.* Slates; mica schists; hornblende schists

Characters of the More Important Metamorphic Rocks

Quartzites. — These range in composition from nearly pure silica to a mixture with 15 per cent or more of aluminum oxide, iron oxide, etc. Quartzites are derived from quartz-sandstones and are characterized by the presence of silica as the cementing agent of the grains, this silica being commonly deposited in crystallographic continuity with the quartz of the grains. Quartzites thus have a crystalline character, and they are harder than ordinary sandstones into which they grade. When much clay was present in the original sandstone, mica, especially muscovite, is developed, producing a micaceous quartzite, which passes by degrees into a quartz-mica schist. A flexible form of micaceous quartzite, in which the grains have a slight power of movement on one another, is called *itacolumite.* Quartz conglomerate, too, may be changed to quartzite and the pebbles may be flattened by dynamic movements.

Quartzites are most abundant in the older (pre-Cambrian) strata, but are not confined to them. They may indeed be of any age.

Slates. — These are mud-rocks or lutytes in which a high degree of slaty cleavage has been developed as the result of compression. This cleavage, as already outlined, has commonly no relationship to the bedding planes, though the name slate is also applied to carbonaceous mud-rocks which split smoothly along the stratification. Mica, especially sericite, and hornblende scales may be developed, but these are not visible except under the microscope. When

they become large and dominant, the slate passes into phyllites and mica schists. (See Fig. 562, p. 638.)

Slates may also be developed from pyroclastic rocks (tuffs) which have been subject to compression without extensive recrystallization. In color, slates generally range from drab to black, but green, red, and purple tints may occur.

The chief uses are for roofing purposes, blackboards, and (formerly) for school slates. The most important American slates are altered Cambrian and Ordovician rocks, but pre-Cambrian and also younger slates occur, the latter chiefly foreign.

Porcelanite, Baked Clay, Hornfels. — Fused clays and shales in the roofs and floors of burned coal seams are changed into a hard, homogeneous rock resembling porcelain and designated *Porcelanite*. Similar results are produced in contact metamorphism, where the shales are baked into a hard, flinty rock to which the name *hornfels* is applied. It breaks in irregular, angular masses, and closely resembles dense trap-rock, for which it may be mistaken. Biotite is commonly an important constituent of this rock, though visible only under the microscope. Various minerals, such as andalusite, garnet, cyanite, staurolite, tourmaline, ottrelite, rutile, hornblende, feldspar, etc., may be developed, sometimes in crystals of considerable size. When the minerals are rather evenly scattered, a knotty slate or hornfels is produced.

Phyllites. — These rocks are intermediate between slates and mica schists, partaking of the structure of the former, but with the development of much fine mica. They may be derived from silicious clay rocks like ordinary slates, but they may also represent altered tuffs or even felsitic rocks. The fine mica scales are commonly sericite, etc., which has also been called hydromica, on which account the name hydromica schist is frequently used.

Mica Schists. — These are schistose rocks in which mica, chiefly muscovite, but also biotite appears in prominent scales, while quartz is the other important mineral. When quartz predominates, the rock passes into a micaceous quartzite. Sometimes the rock is high in lime, when it passes into a micaceous marble or calc schist. Feldspar in greater or less quantity is also present, especially if the schist has been derived from an igneous rock. As accessory minerals, garnet, staurolite, cyanite, sillimanite, tourmaline, apatite, pyrite, and magnetite may be mentioned.

Mica schists are perhaps most commonly derived from the alteration of argillaceous sandstones and silicious shales, etc., but they may also originate from igneous rocks (rhyolites, trachites, etc.). When derived from clastics, they are generally lower in alkalies, and the magnesia is in excess of the lime.

Schists with graphite disseminated through them are not infrequent. These are probably in most cases developed by the metamorphism of carbonaceous shales.

Hornblende Schists. — These are derived from the basic igneous rocks high in ferromagnesian silicates, by the development in them of schistose structure. More rarely, sediments have yielded such rocks by metamorphism, when analysis generally shows a low alumina content and a great excess of magnesia over lime.

While hornblende forms the chief mineral of this rock, biotite, augite, and plagioclase may also be present in varying proportion. Besides these, there

are accessory minerals, such as garnet, magnetite, pyrite, and pyrrhotite, but quartz is normally absent, or at least very rare. By alteration, the hornblende passes into chlorite, with the production of a *chlorite schist.* The plagioclase may be replaced by secondary products, such as epidote, calcite, scapolite, etc. The schistose structure is due to the parallel arrangement of the hornblende crystals. When this structure is indistinct, the name *amphibolite* has been used for the rock. Hornblende schists may form extensive areas by themselves or they may represent the altered basic dikes intruded in more acid rocks with which they have become thoroughly metamorphosed by dynamic disturbances. Such dikes, changed to hornblende schist, abound in the Manhattan Island rocks and are also found elsewhere in the older metamorphic series of eastern North America.

Chlorite Schists. — These are further alteration products of hornblende schists, but may also be derived from other rocks rich in anhydrous iron-alumina silicates. The schistosity is well developed in these rocks and the chief mineral is chlorite, a green, micaceous, and rather soft mineral. More or less quartz is also present, and besides this, plagioclase, talc, epidote, and magnetite may form common accessories. Owing to the pronounced green color, certain of these rocks are sometimes called "green schists." They are not uncommonly members of the metamorphic series of the Appalachian, New England, and Lake Superior regions.

Talc Schists. — These are the metamorphic products of rocks high in anhydrous magnesian silicates but low in iron. The chief mineral is talc, but quartz is also often quite abundant. Feldspars and some micaceous minerals also occur in the latter, and are often difficult to distinguish from the talc scales. The MgO content of these rocks may be 30 per cent or more. It is possible that silicious dolomites in a sedimentary series may in some cases be the original rock from which talc schists are derived. The distribution of talc schists is similar to that of chlorite schists.

Epidote Schists. — These are rarer schists, characterized by the predominance of the mineral epidote. They have a light greenish appearance from the color of the ferromagnesian silicate, epidote, and they are generally the product of metamorphism of pyroxenic and hornblendic rocks. Their CaO and MgO content is often very similar (between 7 and 8 per cent). These schists have a distribution similar to the preceding but are less common.

Graphite Schists. — These are the common product of the metamorphism of carbonaceous sedimentary (clastic) rocks, and they are not uncommon in the metamorphosed Palæozoic series of eastern North America, but also occur in the older rocks. Graphite is present as a rule in only moderate amounts, occurring in scaly flakes along the planes of schistosity. Mica, quartz and feldspar are the common associates in these schists, and when the graphite is present only in small quantities, the rock may be a graphitic mica schist.

Gneiss. — The rocks classed under this term (pronounced *nice*) include a variety of types in which the characteristic gneissic structure is developed. The structure is more coarsely laminated than that of schists, and the rocks split less readily along these planes of lamination. Feldspar is always a characteristic constituent of typical gneisses and, besides this, there occur, as a rule, quartz, mica and hornblende. Many accessory minerals may also occur.

There are, however, gneisses produced from the alteration of basic igneous rocks in which quartz is absent, while the ferromagnesian minerals abound.

Gneisses may be produced from the alteration of igneous as well as clastic rocks. In many cases it is possible to refer the rock back to its original type, but in other cases this cannot be done. According to the rocks from which gneisses are derived, the following types have been recognized:

Original Rock	*Corresponding Gneisses Produced by Metamorphism*
Granite	Granite-gneiss
Syenite	Syenite-gneiss
Diorite	Diorite-gneiss
Gabbro	Gabbro-gneiss
Pyroxenite	Pyroxenite-gneiss
Peridotite	Peridotitic-gneiss
Conglomerate, etc.	Conglomerate-gneiss
Sandstone	Quartzite-gneiss

The conglomerate gneiss of Munson, Mass., a well-known building stone, is so thoroughly crystallized that it is commercially referred to as a granite. The conglomerate was probably originally derived from granites and diorites, and its age appears to have been basal Palæozoic.

Gneiss forms the dominant rock of the old crystalline areas around and upon which the younger sediments were deposited. In America the largest area of such ancient gneisses forms the so-called Canadian Shield. Gneisses also occur in the older Appalachians and in the Cordilleran region. In Europe a similar area is found in the Scottish Highlands, Scandinavia, and Finland. Younger gneisses are also abundant, especially in New England, in parts of Scotland, and in the Alps, where even Mesozoic rocks have been metamorphosed into gneisses by the great dynamic disturbances.

Marbles. — These comprise both crystalline limestones and dolomites, but not all of these have the qualities demanded of commercial marble. Some very slightly altered limestones occasionally furnish this product. All kinds of limestones, of whatever origin, may be changed to marbles, and in this process the original bedding-structure and the fossils are commonly obliterated. When the original limestone was impure, as is usually the case in clastic limestones, silicate minerals, such as tremolite, light colored pyroxenes, various micas, especially phlogopite, etc., are developed as the result of metamorphism. When the original limestone was carbonaceous, the product of metamorphism is a graphitic marble. Sometimes the rock becomes very coarsely crystalline, as in the case of the Westchester dolomite marble, used in the construction of St. Patrick's Cathedral in New York City. (See also Fig. 573, p. 649.)

Marbles abound in the metamorphic districts of the Appalachian belt, especially in Pennsylvania, Vermont, Massachusetts, New York, and Georgia. They are also extensively developed in western Colorado and in the Sierras of California, etc. In the Pyrenees, Alps, Carpathians, and Himalayas many marble quarries exist. The famous Carrara marble is a metamorphosed upper Triassic limestone of the Apennines in North Italy. It is associated with sericite,

chlorite, ottrelite, and mica schists, and is underlain by conglomerate gneisses believed to be of Permian age. The main zone of this marble has a thickness ranging up to 1000 meters. Both white and dark common marble (*ordinario*) make up the main deposit. This, however, incloses locally the famous fine-grained snow-white statuary marble (*statuario*), which comprises about 5 per cent of the entire deposit. The "antique marble" of eastern Greece is included in crystalline schists and is partly metamorphosed Cretaceous limestone and in part belongs to the Archæan. Among the several varieties are the snow-white to yellowish *Pentelic* marble found northeast of Athens, the translucent *Parian* marble from the Island of Paros in the Ægean, of snow-white color with frequently a bluish tinge, uniformly grained, and prized as the finest of all marbles, and others. Great marble deposits also occur in the metamorphic regions of Norway, and good statuary marble has been obtained here. Excellent statuary marble also occurs in the Tyrol (Laas region). Fine marbles for decorative purposes are obtained from various parts of Africa.

Ophicalcites. — These are crystalline magnesian limestones or dolomites, mottled with inclusions of the mineral serpentine in varying amounts, and they mark a transition from marbles to serpentines. In color, the stone is a beautiful mottled green and white. The serpentine is probably derived from crystals of pyroxene which originally were included in the rock, and this may have been a silicious magnesian limestone of sedimentary (clastic) origin, altered by regional metamorphism. The rock is also called *Verd-antique*.

Serpentine. — This is a rock composed of green or red scales, fibers, and massive aggregates of the mineral serpentine, a hydrous silicate of magnesium and iron and generally formed by the static alteration of basic igneous rocks, such as pyroxenites and peridotites. Serpentines vary greatly in texture, and they may contain small quantities of secondary minerals such as chromite, magnetite, garnet, etc. Veins of calcite or magnesium carbonates often intersect the serpentine in all directions and produce a striking appearance. The rock is much used as a building and ornamental stone.

Soapstone or Steatite. — This is a massive talc rock, differing from talc schist mainly in the absence of schistosity. Quartz veins and scattered quartz grains are not uncommon, and magnesium carbonate is also present. The rock often occurs in association with crystalline limestones, as in the Adirondacks, and may be the alteration product of a silicious dolomite or a non-ferruginous basic intrusive igneous rock. Soapstones are of great economic importance, and their distribution is generally similar to that of the crystalline limestones and the serpentines.

Magnetite Rock. — This is a metamorphic product of iron ores, and where found in abundance constitutes a valuable source of iron.

Anthracite, Graphite Rock. — Anthracite is sometimes considered the product of slightly metamorphosed coal beds, but may also originate as an original deposit. The extreme metamorphism of carbonaceous deposits produces graphite, which is pure carbon.

CHAPTER XXI

MOVEMENTS OF THE EARTH'S SURFACE AND THEIR GEOLOGICAL EFFECTS

THE crust of our earth is subject to a variety of movements, some of which are so pronounced and sudden that they produce the tremblings known as earthquakes, while others are slow and gradual, and are only recognized by careful measurements, or by a comparison of the characters of a region at widely separated time intervals, or by special features which indicate them to the trained observer. Among these are the great earth-movements by which areas once land became submerged beneath the sea, while sea-bottoms are upraised into land areas or even into mountain masses of great height and extent.

From a purely geological point of view earthquakes are of less significance than the other movements referred to, but they have a very real interest for us, because they occur practically everywhere and at all times and because their immediate effect upon human welfare is more pronounced than that of any other geological phenomenon. On this account we shall devote more space to them than their geological importance would demand.

SUDDEN CRUSTAL MOVEMENTS — EARTHQUAKES

General Consideration

Earthquakes are the tremors or vibrations set in motion in the outer layers of the earth's surface by sudden disturbances in the crust. These disturbances may be due to volcanic or other explosions, or to local deformation of the crust. They are not infrequently indicated upon the surface by changes in topography, while the tremors resulting from and accompanying the disturbances are often the cause of enormous destruction of life and property, as well as modification of the surface features of the earth. In how far the great disturbances in the earth's crust, of

which we have a record in the rock structures, affected the surface in the past, can only be conjectured, but it is safe to say that most, if not all, of them were accompanied by earthquake tremors, and many of these may have been more violent than any recorded in historic time. It is, however, conceivable that great disturbances may go on slowly, deep down in the earth's crust, and that they are manifested upon the surface only by occasional or intermittent earthquakes, which are due to secondary disturbances, set in motion near the surface of the earth during the progress of readjustment of the rocks at greater depths.

Types of Seismic Disturbances

The name *seismic disturbances* is applied to shocks produced by sudden changes in the earth's crust, and they may be manifested in earthquakes, seaquakes and atmospheric disturbances (air-quakes). Seaquakes and great air-waves may be originated by violent explosions, such as those of the volcano Krakatoa in Java in 1883, where the air-waves passed around the earth several times, while the great sea-disturbances, the so-called *tsunamis*,[1] were noticeable more than five hundred miles away.

The quaking of the lands may also be brought about by volcanic explosions, but the larger earthquakes are probably all produced by dislocations within the earth's crust, and the readjustment of sections under strain. Such disturbances, if near the coast or upon the sea-bottom, are communicated to the water, and thus sea-disturbances or *tsunamis* are also induced. Atmospheric disturbances are, however, as a rule, of slight or negligible importance as effects due to readjustment in the crust.

According to their mode of origin, seismic disturbances, of which earthquakes are the typical expressions, have been divided into the two following groups:

Volcanic or Explosive Earthquakes. — These affect the earth sea and air. As a subordinate type, the disturbances due to explosions of gases in coal mines, gas reservoirs, etc., and the concussions due to the detonations of artificial explosives either on land or in the sea or air may be included. Such explosions affect chiefly the air and the water, though minor tremors may be induced by them in the rocky crust of the earth.

[1] A word of Japanese origin for the great seismic waves often wrongly called "tidal waves."

Dislocation, Fault or Fracture Earthquakes. — These produce the larger seismic disturbances of the land and are communicated to the sea as well, but affect the air only to a minor degree. The actual dislocation is probably the accompaniment rather than the cause of the shock, this being produced chiefly by the sudden fracturing of the rock along a line where strains have accumulated until they exceed what the strength of the rock can withstand. As a subordinate type, the tremors due to the collapse of the roofs of caves, such as frequently characterize the "Karst" region of the former Austrian Coast-land, may be cited. They affect chiefly the land, but only to a minor degree. Tremors due to the collapse of buildings form another subordinate type.

While even these subordinate tremors may become of great human or economic importance, they are insignificant in their geological effects, and we may confine our attention primarily to the disturbances due to volcanic explosions and those due to dislocations of the earth's crust, and chiefly to the latter.

Centers and Areal Extent of Disturbances

In the case of disturbances due to volcanic explosions, we may consider that they center about a circumscribed spot or point, which is termed the *focus* or the *hypocenter* of the earthquake (also called seismic center, centrum or origin). In the case of a dislocation, the disturbance extends along a line, though it may be most violent at one or several points along that line. In general, the shock appears to originate comparatively near the surface, so that the focus or center is probably never deeper than 30 geographical miles, and probably does not, as a rule, exceed 5 to 15 miles. The point or locus upon the earth's surface immediately above this focal point or line is called the *epicenter* or the epicentral or epifocal point or line.

Earthquake Waves. — The disturbance at the focus starts a series of vibrations or *earthquake waves* which rapidly spread from this point through the earth in ever widening spheres (Fig. 574).

The rate at which such vibrations travel is enormous; they will pass through the 8000 miles of the diameter of the earth in 20 to 22 minutes, or at the rate of about 375 miles per minute. The rate of transmission, however, varies with the depth. From data afforded by the California earthquake of 1906, Reid has calculated that while the transmission at the surface was 4.5 miles per second, at 272 miles below the surface it was 6 miles per second; at 612 miles

depth, 6.9 miles per second; at 1225 miles, 7.8 miles per second; and at 1968 miles depth, it was 7.9 miles per second. This relatively lessening rate of in-

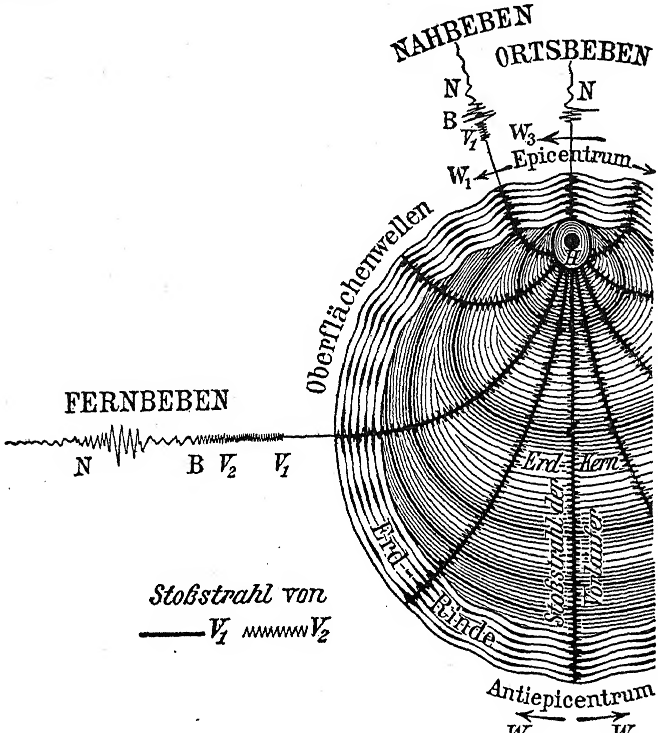


FIG. 574. — Diagrammatic representation of the propagation of the earthquake waves and their record by the seismograph in different parts of the earth. (After Sieberg, from Keilhack's *Praktische Geologie.*)

Explanation and translation of terms: *H*, hypocentrum; *Ortsbeben*, local vibration (at epicentrum); *Nahbeben*, vibrations not far distant; *Fernbeben*, distant vibrations; *Stoss-strahl*, the "wave normal," represented by the heavy lines which extend outwards from the hypocentrum (*H*) in all directions at right angles to the successive wave lines (shown by the fine lines in the figure) and along which a vertical movement takes place. V_1, V_2, first and second preliminary vibrations (*Vorläufer*); W_1, surface waves sent from the epicentrum; W_2, surface waves returned from the antiepicentrum; W_3, third set of waves (rarely recorded) sent out again from epicentrum; *B*, principal or great vibrations; *N*, aftervibrations (*Nachläufer*); *Oberflächenwellen*, surface waves; *Erd-Rinde*, earth's crust; *Erd-Kern*, earth's center.

crease with depth indicates that the density and elasticity of the earth's crust increases with depth, down to a certain point.

Earthquake waves may be resolved into their longitudinal or compressive components which vibrate in the direction of the propagation of the shock,

and into the transverse components which vibrate at right angles to the direction of propagation. To record these waves, special instruments called *seismographs* are devised (Fig. 575 *a*), in which three heavy pendulums are suspended in such a way that they will record the three movements at right angles, N. and S., E. and W., and up and down, though in many seismographs the latter is omitted (Fig. 576). The weight of the pendulums keeps them stationary for a

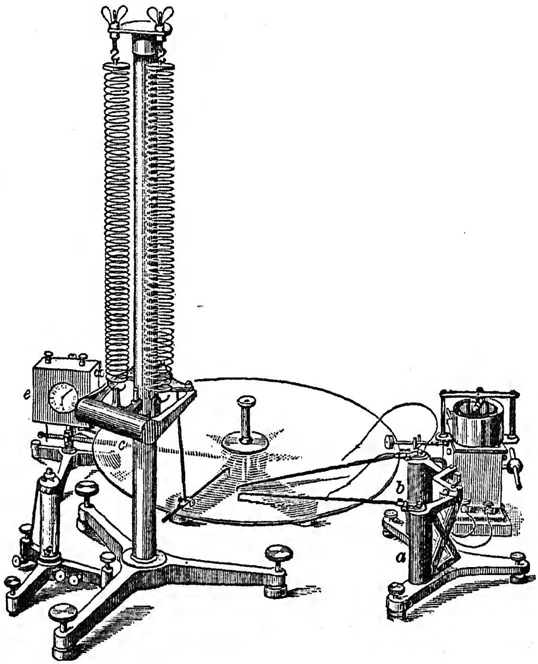


FIG. 575 *a*. — The Ewing seismograph, constructed to record all three movements (University of California, after Le Conte). Three pendulums are arranged to swing in the manner of a bracket or a gate, in three planes, at right angles to one another. Two of them are placed vertically and oscillate in a horizontal manner. *a*, position north and south records east-west movement; *b*, position east and west records north-south movement; the third, *c*, oscillates in a vertical manner, being placed in a horizontal position and being retained by sensitive spiral springs. Styles from these pendulums make the record on a circular smoked-glass plate rotating in a horizontal plane. (Fig. 575 *b*.) *d*, driving clock; *e*, time-recording clock.

long time, while the earth vibrates beneath them. The point of a pencil inserted in the pendulum makes the record upon sheets of paper which are moved by clockwork at a regular rate. These records are called *seismograms*, and two or three are formed for each earthquake, according to the construction. They consist of a series of wave-like or zigzag lines crossing the central line of the paper, and their amplitude records the varying magnitude of the vibration.

Thus a record made on the side of the earth opposite that of the epicentrum (Fig. 577 *b*) will record first a series of minor or preliminary tremblings (V_1, V_2),

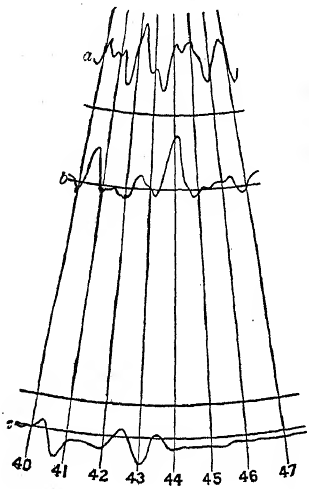


FIG. 575 *b*. — Part of record made by Ewing seismograph. *a*, east and west motion; *b*, north and south motion; *c*, up and down motion. (After Sekïya from Le Conte.)

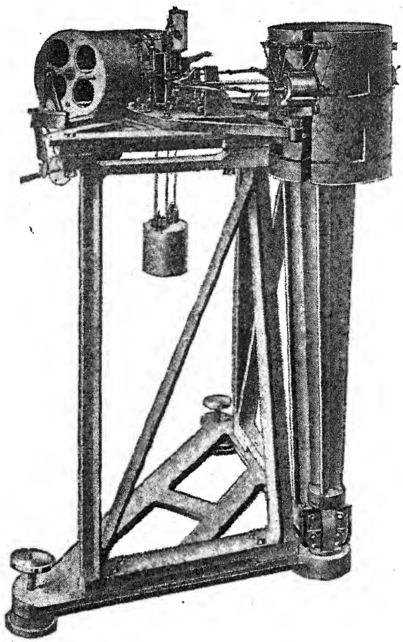


FIG. 576 *a*. — Seismograph recording two horizontal movements (Spindler and Hoyer, Manuf. Göttingen). A cylindrical mass or pendulum weighing from 80 to 200 kilograms is supported on a vertical pillar about 1 meter long, which is hinged at the base to one side of the framework so as to permit motion in two directions at right angles. From the center of gravity of the pendulum mass extend two horizontal shanks, oriented respectively in a north-south and east-west position, and which through the medium of two levers operate two styles or markers. These rest upon a cylinder, covered with smoked paper (see Fig. 576 *b*), which revolves on its horizontal axis under the influence of a weight. During an earthquake the suspended mass, owing to its inertia, remains immobile with reference to the vertical, and with it the shanks which bear the levers and styles, while the framework with the recording cylinder moves with the oscillations of the earth. The levers amplify the movements, which are recorded upon the cylinder in two sets of lines, one representing the east-west and the other the north-south movement. From a practical viewpoint the framework and recording cylinder remain stationary, while the articulated pendulum with the shanks, levers, and styles sways with the earth movements. (After Stanislas Meunier. Courtesy of *Popular Science Monthly*.)

which appear at the antiepicentrum 20 to 22 minutes after the shock. These are followed by the strong vibrations of the principal shock (B), and these, in

turn, are followed by the feeble vibrations of the dying shock (*N*). The preliminary tremors are recorded only at points more than 1000 kilometers from the seat of disturbance, and they are believed to have come by the shortest path through the earth, or in general along the direction of the chord between the seat of disturbance and the recording station (*Stoss-strahl*, Fig. 574), while the larger waves travel by a longer route over the surface (*Oberflächenwellen*, Fig. 574).

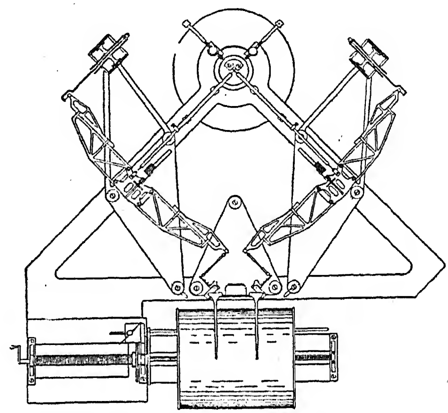


FIG. 576 *b*. — Diagrammatic view, from above, of the seismograph shown in Fig. 576 *a*. (After Stanislas Meunier. By courtesy of *Popular Science Monthly*.)

These earthquake waves represent actual vibratory movements of the rock particles, such movements being extremely complex and in all directions (Fig. 578). The distance to which the particles vibrate from their original point of rest, or, as it is called, the amplitude of the vibration,

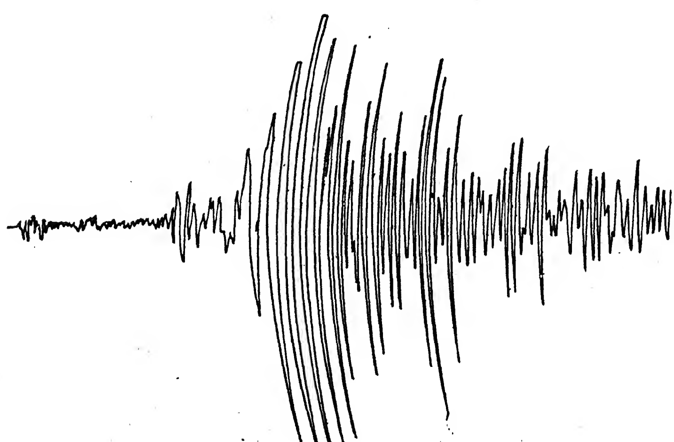


FIG. 577 *a*. — One of the seismograms of the Messina earthquake of December 28, 1908, as registered at Göttingen, Germany, by the seismograph illustrated in Figs. 576 *a*, *b*. (After Stanislas Meunier. By courtesy of *Popular Science Monthly*.)

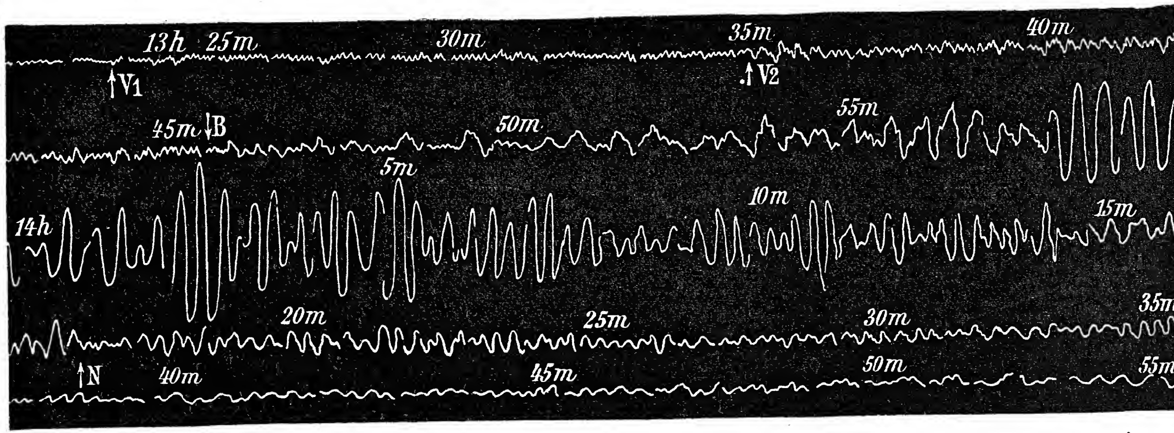


Fig. 577 *b.* — Seismogram of the San Francisco earthquake of April 18, 1906, as recorded in Strassburg in Alsace, a distance of about 130 degrees. (After Sieberg, from Kayser's *Lehrbuch.*) The shocks began at San Francisco at 5.12 A.M., or at 1.12 P.M., Strassburg time. The preliminary record thus begins about 13 minutes later (13 h., 25 m. = 1.25 P.M.) but the heavy record did not begin until about 43 minutes later. The preliminary tremblings passed approximately along the path indicated in the diagram, Fig. 574, by the normal (*Stoss-strahl*) next to the one from the hypocentrum (*H*) to the antiepicentrum. V_1, first preliminary shocks; V_2, second preliminary shocks; *B*, main shocks; *N*, aftershocks. (13 h. = 1 P.M. Strassburg time; 14 h. = 2 P.M. *ibid.*)

is seldom very great, though the surface waves produced in water or unconsolidated rock material or soil are often pronounced. Water waves 40 feet in height and piling up on the coast to 60 feet were produced by the Lisbon earthquake of 1755, and the loose alluvial material of the Mississippi Valley bottom was thrown into such wave-like commotions during the New Madrid earth-

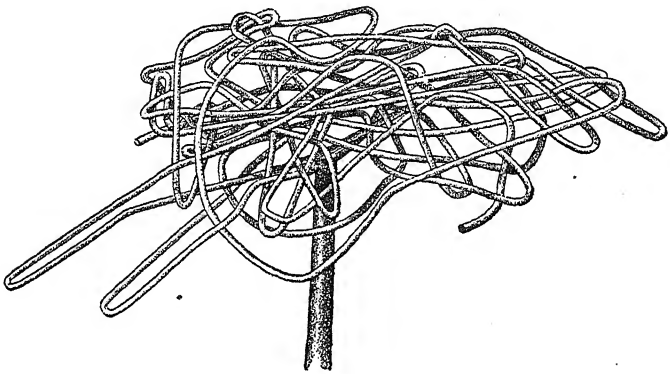


FIG. 578. — Model of a part of the path traveled by a particle on the earth's surface during the earthquake of Tokyo, January 15, 1887. (After Seikei Sekīya.) This model is constructed by the combination of the three movements recorded by the Ewing type of seismograph.

quake of 1811 that the trees bent over and interlocked with their branches. Here the actual movement of the particles of the solid underlying rock, or the amplitude of vibration, was probably not over a few centimeters. It has been ascertained that the amplitude of the vibration of rock particles in earthquakes of sufficient violence to destroy an entire city is often not greater than 20 millimeters, or about three fourths of an inch, while amplitudes of half or even one quarter that amount are productive of destructive effects. The pronounced effects of earthquakes are produced by the suddenness of the shock rather than by the amount of motion of the rock particles.

Great Earthquakes of Modern Times

In order that the student may gain some concrete understanding of earthquakes and the phenomena accompanying them, we will briefly review some of the more violent earthquakes of modern times, after which the main characteristics may be summarized.

The Lisbon Earthquake of 1755

One of the most destructive earthquakes which has visited Europe in historic times was that which, on November 1, 1755, devastated the city of Lisbon, Portugal. Without previous warning, except for a thunderous underground noise immediately before the shock, the greater part of the city was laid in ruins, and 60,000 persons perished within the next six minutes. The sea retired abruptly, laying bare the bar off the coast, and then rolled back over the land as a huge series of waves, rising 50 feet or more above its ordinary level. The shock was marked in the mountains of Portugal, which seemed to rock, while fissures opened at the summits of some of them, rending them in a most intricate manner, huge masses being precipitated into the valleys below. Flames appeared to issue from these clefts, apparently the play of electrical phenomena, and clouds of dust gave the appearance of smoke.

A new quay built entirely of marble, upon which many persons had congregated for safety, sank suddenly, carrying the hapless mortals with it, and of their bodies not one is said to have floated again to the surface. Many boats and small vessels anchored near by, and filled with people, were swallowed by the waters, the depth of which in the region of the quay became 100 fathoms or more. The lower part of the city and the quay were built upon the blue clay and other Tertiary and younger strata at the mouth of the Tagus River, and it was the structures thus located, which suffered chiefly, not a building upon the Mesozoic limestones or the basalts being injured.

The shock of this earthquake affected a portion of the earth's surface estimated to have been four times greater than the extent of Europe. It was felt in the Alps, on the coast of Sweden and elsewhere on the Baltic, over much of north Germany, in Thuringia and in Great Britain, where the water of Loch Lomond in Scotland rose suddenly over two feet against the banks and then subsided below its usual level. At Kinsale in Ireland a body of water rushed into the harbor, whirling around vessels there stationed, and pouring into the market place. In the West Indies, where the tide is usually only two feet high, the water rose suddenly by more than 20 feet, appearing discolored and of an inky blackness. Even in the region of the Great North American Lakes the shock was felt. It was, of course, most violent in the Mediterranean region,

the agitation being as marked in Algiers, north Africa, and in Morocco as in Portugal and Spain. Many persons (8000 to 10,000 in one district) were said to have been swallowed up by fissures which opened and closed again. Even at a distance out at sea, the shock was felt on the decks of vessels, being so violent at a point 40 leagues west of St. Vincent that the men were said to have been thrown a foot and a half perpendicularly up from the deck. A great sea wave or *tsunami*, originating on the ocean floor 50 or more miles off the coast of Lisbon, and estimated to have been 60 feet high at Cadiz, swept the coast of Spain. It was followed by others of decreasing heights. At Tangier, Africa, the water rose and fell 18 times; on the Madeira coast (at Funchal) it rose fully 15 feet above high-water mark, the tide at the time being at half ebb. Several of the coast cities were flooded. It took the sea-wave 2½ hours to reach the Madeira coast, although the shock was transmitted through the earth in 25 minutes. This shock caused no retreat of the sea there on account of the steepness of the coast. The effects of those waves were felt even on the shores of the West Indian Islands across the whole expanse of the Atlantic.

The Calabrian Earthquake of 1783–86, and the Messina Earthquake of 1908

The Calabrian peninsula of Italy (Calabria Ultra) (Fig. 579 *a*) was the scene of a violent series of earthquake shocks, which began in February, 1783, and lasted for nearly four years — to the end of 1786. This is the first of the great earthquakes the effects of which were carefully noted by men of scientific training. The convulsions extended not only over the whole of Calabria Ultra, but also over the southeastern part of Calabria Citra and across the sea to Messina, affecting an area of about 500 square miles. The concussions were noted over a great part of Sicily and as far north as Naples.

The formations covering the area chiefly affected consist of thick argillaceous beds with marine fossils and some sands and limestone, all of Tertiary or younger age and abutting against the central Apennine chain of granite and other rock. The Calabrian plain formed by these Tertiary and younger rocks is flat and level except where dissected by streams, which have cut gorges, in places

600 feet deep, and with steep, sometimes almost perpendicular sides, due to the binding together of the upper beds by roots of trees, etc.

The greatest destruction occurred within a radius of 22 miles of the city of Oppido in Calabria Ultra. The first shock, which occurred on February 5, 1783, " . . . threw down in two minutes the greater part of the houses in all the cities, towns, and villages, from the western flanks of the Apennines in Calabria Ultra to Messina in Sicily, and convulsed the whole surface of the country" (Lyell). A second shock of almost equal violence occurred on March 28, and this rudely shook the granite chain which passes through Calabria from north to south, and which was only slightly shaken by the first shock. Along the flanks of this chain the soil slid downwards, producing a chasm from 9 to 10 miles in length between the solid granite and the sandy soil. These landslides were sometimes carried for considerable distances over the lower ground, thus causing the properties of different individuals to become superimposed and leading to subsequent disputes of ownership. The chasm along the mountain base has been explained as caused by the reflection and refraction of the earthquake wave in passing from a body of low elasticity, such as the clay and gravel, to one of high elasticity like the granite, a shock being thus produced in the opposite direction.

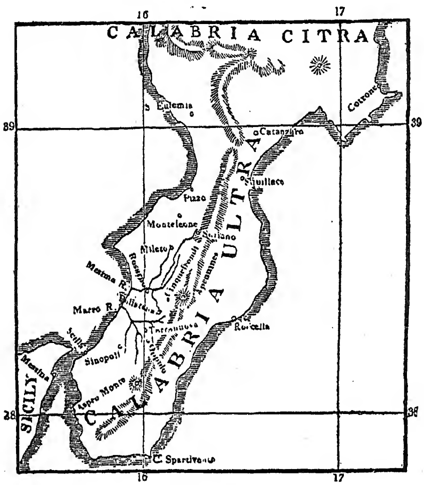


FIG. 579 *a.* — Map of Calabria, showing the regions chiefly affected by the earthquakes. (After Lyell.)

The surface of the plain was thrown into undulating movements by each shock to such an extent that rooted trees are said to have touched the ground with their branches, a fact attested by competent authority. A vorticose movement was indicated by the behavior of the large stones of two obelisks at the convent of

St. Bruno, the pedestals of which remained in position while the separate stones were partly rotated horizontally (Fig. 579 *b*). Pavement stones in many towns were thrown up and overturned, and a round tower at Terranuova was faulted through the center (Fig. 579 *c*). Along this fault-line houses on one side were lifted above those of the other, which sank with the ground, and walls crossing it were faulted, yet with sides so firmly adhering that the fault was only marked by the displacement of the tiers of stone on opposite sides. In this town, too, a stone well was apparently driven from

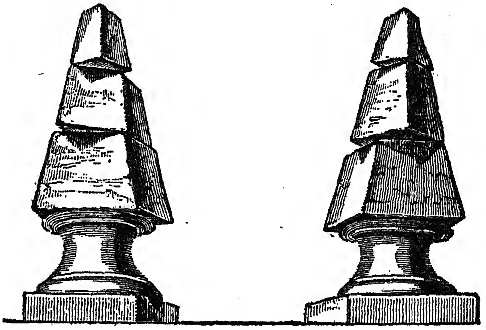


FIG. 579 *b*. — Shifts in the two obelisks in the convent of St. Bruno, Calabrian earthquake of 1783. (After Lyell.)

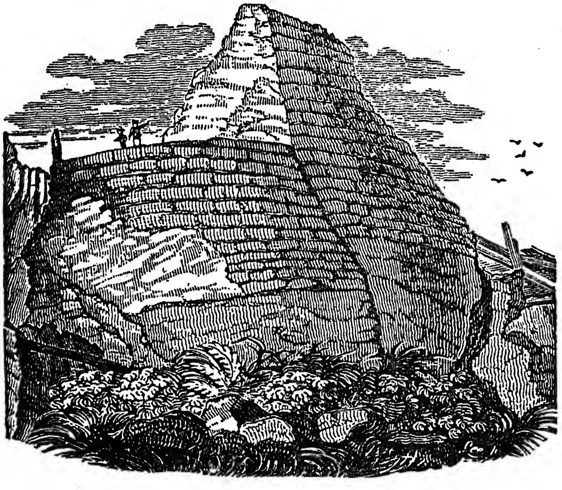


FIG. 579 *c*. — Fault in the round tower of Terranuova in Calabria occasioned by the earthquake of 1783. (After Lyell.)

the ground, resembling a small tower eight or nine feet in height, and a little inclined. This was probably effected by the settling of the soil around the stone well. In Monteleone, some streets

had all their houses but one thrown down, others all but two, these excepted buildings being often scarcely injured. In many Calabrian cities all the more solid buildings were destroyed, the lighter ones escaping, but the reverse was true at Messina and elsewhere.

Rents and chasms were opened and closed again along the path of the earthquake, engulfing houses, cattle, and human beings, but in a few cases, it was stated, individuals thus engulfed were thrown out again, sometimes still alive, by an immediately following shock. Radiating fissures were formed in many places and the surface of the country was broken by cracks resembling those of a shattered pane of glass.

In the central district around Oppido, many houses were completely engulfed in the opening and closing fissures, while at Cannamaria ". . . four farm houses, several oil-stores, and some spacious dwelling houses were so completely engulfed in one chasm, that not a vestige of them was afterwards discernible " (Lyell). Similar phenemona occurred elsewhere, and later excavations showed that detached parts of the buildings and their contents were so firmly jammed together by the closing of the fissure that they formed one compact mass. Many fissures closed more gradually, several near Mileto, which had engulfed an ox and nearly one hundred goats, being, when later visited, still nearly a foot in width. One fissure, however, on a hillside near Oppido, which had swallowed part of a vineyard and a considerable number of olive trees with much soil, remained open for a length of 500 feet and a depth of 200 feet. Many fissures formed by the shock of February 5 were greatly widened, lengthened, and deepened by the shock of March 28, some of them becoming nearly a mile in length by from 150 to 200 feet in depth. They were usually straight, but sometimes crescent form.

But the most remarkable features formed were numerous small craterlets or funnel-shaped sinks, of about the size of a carriage wheel or larger, which covered parts of the plains (Fig. 579 *d*). These were in some cases filled with dry sand, in others with water which arose through a neck or tube at the base. Innumerable cones of sand were thrown up in marshy places by the spouting upward of the water in jets. Rivers were dried up by the violent shocks, but immediately afterward overflowed their banks. River courses were deranged by extensive landslides, and 215 lakes and small

ponds were formed. In one case, a river valley was transformed by a landslide into a lake two miles long and one mile broad. Oaks, olive trees, vineyards, and corn slid with the land into the river-valley at Terranuova, where they continued to grow as did those of the portion from which they were detached at least 500 feet higher and about three quarters of a mile distant. Near Seminara an extensive olive orchard was hurled to a distance of 200 feet into a valley 60 feet in depth, the region from which it was detached opening in a deep chasm which was appropriated by the river,

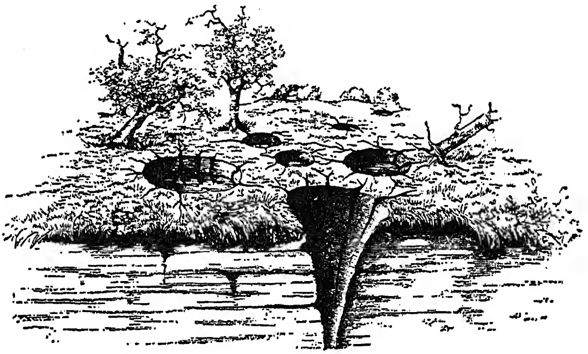


FIG. 579 *d.* — Craterlets formed during the Calabrian earthquake of 1783. (From C. Vogt.)

leaving its former channel completely dry. On this mass of earth stood a small house, which was carried down with it entire and without injury to its inhabitants. The olive trees thus transported bore an abundant crop of fruit the same year. The greater part of the town of Polistena, "consisting of some hundreds of houses, travelled into a contiguous ravine and nearly across it, about half a mile from their original site," and several of the inhabitants were dug out of the ruins alive and unhurt. Near Mileto, two tenements, "occupying an extent of ground about one mile long and half a mile broad, were carried for a mile down a valley." Here the ground had been long undermined by rivulets. A thatched cottage and large olive and mulberry trees were carried uninjured for this same distance, most of the trees remaining erect.

In many places mud-streams were formed which buried houses and trees in their paths. In one case two such mud-streams, rolling forward like streams of lava, united in a valley, forming a

stream 225 feet wide and 15 feet deep, and before it ceased to move it covered a surface one Italian mile in length. "In its progress it overwhelmed a flock of 30 goats and tore up by the roots many olive and mulberry trees, which floated like ships upon its surface" (Lyell). This mud was highly calcareous, and it gradually dried and hardened, the mass decreasing 7½ feet in thickness.

Along the straits of Messina, near the famous rock of Scylla, huge masses of rock were detached from the lofty cliff and overwhelmed many gardens and villas. "At Gian Greco, a continuous line of cliffs, for a mile in length, was thrown down. The sea was violently agitated, and rising more than 20 feet rushed back and forth over the low coast, causing great destruction of life. The aged prince of Scylla, and 1430 of his people, who had taken to the fishing vessels for safety, perished, all the boats being destroyed."

The total number of persons that perished by this earthquake in the two Calabrias and Sicily was estimated at 40,000, and about 20,000 more died from epidemics caused by insufficient nourishment and exposure, and by malaria arising from the new stagnant pools. Many people were burned to death, as numerous fires resulted, and many were swallowed alive by the fissures which opened and closed and might have been saved if help had been at hand. But by far the greater number perished in the ruins of their houses, while on the coast drowning was the chief cause of death.

This same region, along the straits which separates Sicily from the mainland of Italy, was visited by the most destructive earthquake of modern times on December 28, 1908. The cities of Messina and Reggio were completely destroyed, and so were many smaller towns and villages. The whole of Calabria and of eastern Sicily was affected by the shock. The catastrophe has been called the most appalling of its kind that has visited any country. The number of persons killed was approximately 78,000, while the number of injured was beyond calculation.

The New Madrid (Missouri) Earthquake of 1811–12

On March 26, 1812, violent earthquake shocks destroyed the city of Caracas, Venezuela, and previously to this and continuing for some time after, earthquake shocks were felt in South Carolina and in the valley of the Mississippi from New Madrid to the mouth of the Ohio in one direction, and to St. Francis, Arkansas,

in the other. At New Madrid, subterranean rumblings had been heard frequently for many years before and up to within a year of the earthquake. The first great shock came about 2 o'clock in the night of December 16, 1811, accompanied by a noise like thunder, and in a few minutes the air was saturated with sulphurous vapors. Between December 16, 1811, and March 16, 1812, a total of 1874 shocks was recorded, eight of them being of the first order of intensity. The most violent one occurred on February 7 and was accompanied by sulphurous vapors and unusual darkness.

The region affected is a part of the flood plain of the Mississippi and is underlain by unconsolidated sands and muds. The quaking of the ground continued for several successive months, and great changes in the surface were produced. Large lakes were formed, sometimes in the course of an hour; others already in existence were drained. The most noted of these newly formed water bodies is Reelfoot Lake, in Obion County, northwest Tennessee, which has a length of more than 20 miles and a width of 7 miles, while the water in places covers the tops of submerged cypress trees which grew on the ground before it settled. Near Little Prairie, a lake many miles in length but only from 3 to 4 feet in depth came into existence. Later it disappeared, leaving behind a stratum of sand. Lake Eulalie, near New Madrid, 300 yards long and 100 yards wide, was suddenly drained through parallel fissures which opened in the bottom and which were not yet closed when Lyell visited the region 34 years later. The ancient bed of the lake is now largely overgrown with forest trees.

During the first shock, the current of the Mississippi River was reversed in direction north of New Madrid, continuing so for several minutes. During later shocks, mountainous waves were generated in the river, which receded from its banks, leaving boats high upon the sand, and then moving forward as a wall of water 15 to 20 feet high, tore them from their moorings and swept them into a creek as a close-packed mass, a quarter of a mile long. The graveyard at New Madrid was precipitated into the bed of the Mississippi; and the ground on which the town is built, and the river bank for 15 miles above it, are said to have sunk eight feet below their former level. The trees of the region suffered breaking, and many were inclined in all directions, continuing to grow thus. Many fissures were opened, usually in a northeast-southwest

direction, and much water, sand, and lignite was discharged, often with great force. Hundreds of these chasms were still visible in the alluvial soil seven years after the event, and Lyell noted many of them only partly filled 35 years after their formation.

Numerous circular craterlets or sinkholes, from 10 to 30 yards wide and 20 feet in depth, appeared. These were located on the border of the "Sunk Country," west of New Madrid, which extends along the course of the White Water and its tributaries for a distance of between 70 and 80 miles north and south and 30 miles east and west. In this area innumerable dead trees are submerged, some erect, but many prostrate. The borders of the submerged area are gradually filling up by growth of swamp vegetation and sediments washed into it. East of this area a low dome, 20 miles in diameter and rising 20 or 25 feet above the alluvial plain, was formed.

In this case also the trees are said to have bent down during the shocks, many of them becoming interlocked with the branches of other trees similarly bent, and being thus prevented from righting themselves again. One result of the disturbance due to this earthquake was the great confusion into which boundary lines were thrown, so that the government found it necessary to resurvey an area of 1,000,000 acres.

The Chilean Earthquakes of 1822 and Later Periods

Chile has been visited by many earthquakes, of which those of 1822, 1835, and 1906 are especially noteworthy. The coastal region (Fig. 580) was visited by a particularly destructive earthquake on November 19, 1822, which was felt simultaneously for a distance of 1200 miles north and south. Much damage was done in Valparaiso, Santiago, and other places, and the coast near Valparaiso was raised from three to four feet above its former level, exposing beds of oysters, while mussels and other Mollusca and seaweeds adhering to the rocks were left high and dry. Vast quantities of fish were killed and their bodies left to decay over the raised ground. The slopes of streams back of the coast were increased, one of them gaining a fall of 14 inches in little more than 100 yards. This indicates a greater inland rise, which was estimated to be from five to six or even seven feet at a distance of a mile from the coast. Parallel fissures opened in the granitic rocks

inland. As in the Calabrian earthquake, cones of earth up to four feet in height were built up on alluvial soil by water, mixed with sand, being forced through funnel-shaped openings. The houses built on alluvial soil were more damaged than those built upon the granite.

The total area elevated during this earthquake is estimated at 100,000 square miles, an area equal to half that of France. Accepting this estimate, Lyell figured that the entire mass of land raised above sea-level was 57 cubic miles in bulk, and of a weight 100,000 times that of the great Pyramid; and if a moderate estimate of the weight of the entire mass displaced is made, assuming the depth affected to be two miles, it would be 3630 times that much. Lyell has further estimated that the amount of solid matter thus raised above the sea-level by this single earthquake is equal to that which the Ganges River would carry into the sea during a period of four centuries.

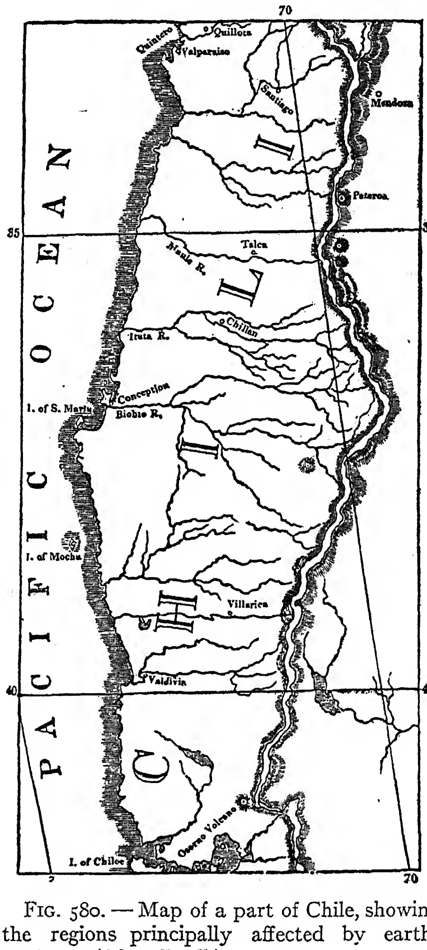


FIG. 580. — Map of a part of Chile, showing the regions principally affected by earthquakes. (After Lyell.)

The shocks continued at intervals of 24 to 48 hours for nearly a year, or until the end of September, 1823. Twelve years later, on February 20, 1835, another great earthquake visited this coast, being felt for nearly a thousand miles from north to south between Copiapo, 400 miles north of Valparaiso, and Chiloe, and for about

500 miles east and west from Mendoza to the island of Juan Fernandez, 365 miles from Chile. Its effects were particularly noted in Concepcion Bay, where the sea retreated, stranding vessels which lay in seven fathoms of water, and then rushed in again with several repetitions, the waves being thrown 16 to 20 feet in height and rushing far up on the shelving beach. Large numbers of cattle were washed into the sea by these waves, and others standing on a steep slope near the shore were rolled into the sea by the shock.

Upward of a hundred villages were destroyed on the coast and the islands of the bay, and rocks broken off beneath the sea were cast high upon the shore. Darwin found one of them to have a length of six feet, a breadth of three, and a thickness of two feet. On Quiriquina Island, Darwin found many fissures extending in a north-south direction, some of them a yard wide. The hard, slaty rock of the island was shivered superficially as if blasted by gunpowder, and huge blocks were precipitated to the beach, others being loosened and left in a position where the heavy rains would tend to their further displacement. Darwin believed that this single convulsion "has been more effectual in lessening the size of the island of Quiriquina than the ordinary wear and tear of the sea and weather during the course of a whole century."

The island of Santa Maria, about 25 miles southwest of Concepcion, and about seven miles long by two broad, was raised ten feet at the northern and eight feet at the southern end, as shown by the mussels which were found clinging to the steep faces of the rock. A large flat at the northern end of the island, formerly submerged, became permanently exposed, causing the extermination of great beds of shellfish, while the water all around the island was diminished in depth by a fathom and a half.

The great sea waves or tsunamis which originated from this earthquake "traversed the ocean to the Society and Navigator Islands, 3,000 and 4,000 miles distant, and to the Hawaiian Islands, 6,000 miles away" (Dana). The velocity of such waves is very great, one originating in the earthquake of 1868 running to the Hawaiian Islands at a rate of 465 miles per hour.

During the earthquake of 1835 and for some time preceding and following it, the whole volcanic chain of the Chilean Andes, 1300 miles in length, was in a state of unusual activity. Lava flowed from the crater of Osorno at the southern end, and a submarine

volcano broke out about a mile from the island of Juan Fernandez (365 geographical miles from Chile), this island being violently shaken and devastated by a great wave.

Another earthquake shock occurred at Concepcion in November of the same year, and at the same time the volcano Osorno, 400 miles distant, renewed its activity.

Two years later, on November 7, 1837, Valdivia, situated near the coast about 300 miles south of Concepcion, was destroyed by a violent earthquake, and the sea-bottom near the island of Lemus in the Chonos Archipelago was raised more than eight feet.

In August, 1906, the coast of Chile was subjected to another severe earthquake which did much damage in Valparaiso and other places, killing several thousand persons. After-shocks continued for a long time, while the readjustment along the fault lines took place.

The New Zealand Earthquake of 1855

New Zealand has been visited by many earthquakes, which have caused profound alteration of its surface and coast line. One of the most marked of them occurred on the night of January 23, 1855, being most violent in the narrowest parts of Cook Strait, between the two main islands (Fig. 581), and affecting an area of land and water estimated at 860,000 square miles — three times the size of the British Islands. Near Wellington, in the North Island, a tract of land comprising 4600 square miles was permanently upraised from one to nine feet. The uplift was especially marked along the eastern flank of the Rimutaka Mountains, a range running northeast from Cook Strait, and rising to heights of 4000 feet above the sea. A fault scarp came into existence along the eastern face of the range, and where shown at the Muka Muka cliff, on the coast, 12 miles southeast of Wellington, it was found that the older rocks of the mountains had experienced an elevation of nine feet, while the Tertiary rocks on the east remained undisturbed (Fig. 582). The elevation of the older rock on the west of the fault was clearly marked by a line of nullipores or calcareous seaweeds, originally at sea-level, but immediately after the shock nine feet above it. A beach 100 feet wide also came into existence at the foot of this cliff, where formerly the water had washed it closely at high tide.

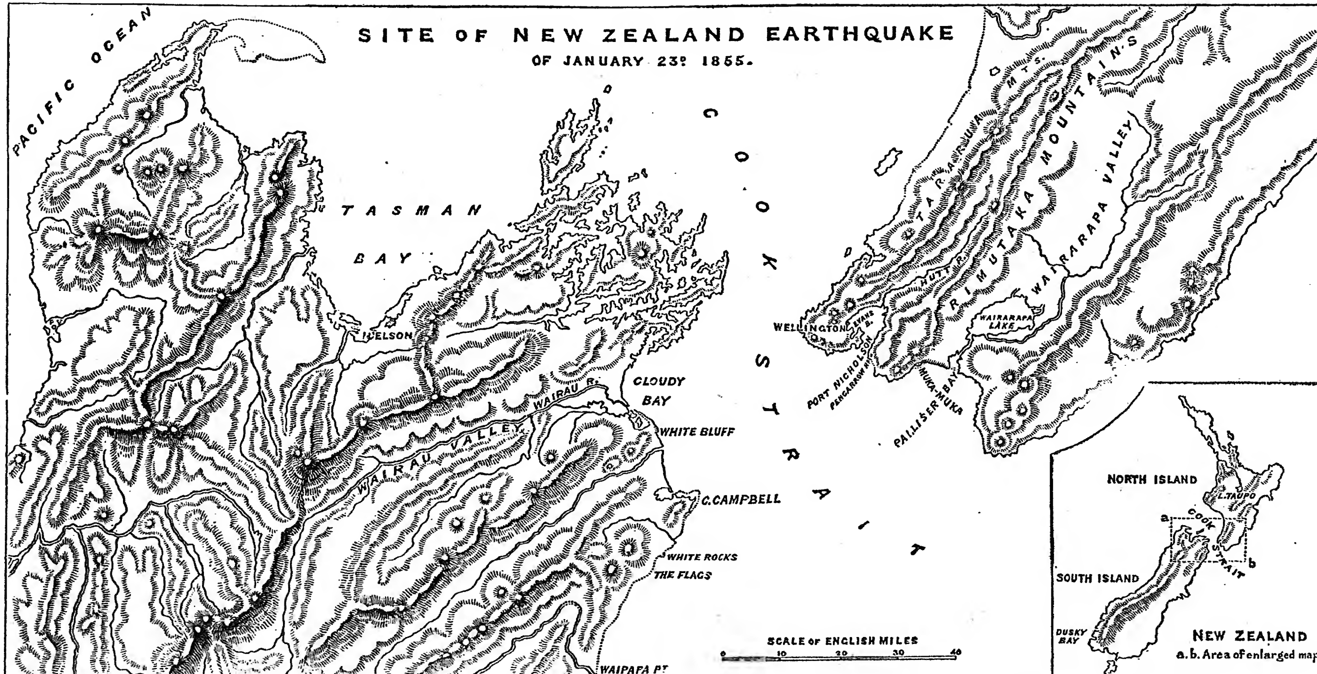


FIG. 581. — Map of Cook Strait, New Zealand, the site of the earthquake of 1855. (After Lyell.)

The fault scarp extends continuously into the interior of the country along the base of the Rimutaka Mountains, being marked by nearly perpendicular fresh cliffs nine feet in height, and traceable for a distance of about 90 miles. In many places the fault line was marked by an open fissure from six to nine feet broad and filled locally with soft mud and loose earth.

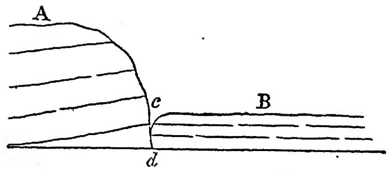


FIG. 582. — Section of Muka Muka cliff, Cook Strait, New Zealand, showing recent fault. *A*, argillite; *B*, Tertiary beds; *c*, line of fissure and fault. (After Lyell.)

The effects of the elevation were also seen at Port Nicholson, about 12 miles west of Muka Muka cliff, the elevation there being five feet on the eastern and four feet on the western side of the harbor. We have here an interesting example of block faulting or the tilting of a great block of the earth's crust by differential elevation. It is also significant that although the fault plane was apparently vertical, the strata on the east remained undisturbed and without change in position, while the block was actually raised along the fault plane. Thus the fault is really an upward thrust although it has the appearance of a gravity fault.

Owen's Valley, California, Earthquake of 1872

Owen's Valley lies in eastern California near the eastern base of the Sierra Nevada Mountains. The earthquake occurred on March 26, 1872, and the ground sank in strips producing several fault scarps, the principal one of which followed the base of the mountains, and in places rose to 20 feet and extended for about 40 miles. Opposite the highest point a second scarp appeared 10 feet high and facing in the opposite direction. Other parallel faults were formed and an area of several thousand acres of land was not only lowered bodily, but also shifted northward for about 15 feet. At Big Pine, many extensive fissures were opened, traceable for several miles, while an area of ground 200 to 300 feet wide sank in places to a depth of 20 feet or more, leaving vertical fault scarps on opposite sides. This depression was filled with water, forming a pond one third of a mile in length. A road crossed by

a north-south fissure had the part to the west of the fissure shifted 18 feet to the south.

The earthquake consisted of only one violent shock, and all the changes were produced within a few seconds. After-shocks and slight tremors, however, continued for two months longer.

The Charleston Earthquake of 1886

On August 31, 1886, a violent shock visited the city of Charleston, S. C., at 9:51 P.M., there having been two light premonitory shocks on the 28th and 27th preceding. About 14,000 chimneys were thrown down, and in some streets walls and roofs of buildings collapsed. The shocks lasted a little more than half a minute, the greatest destruction being accomplished in the first twenty seconds.

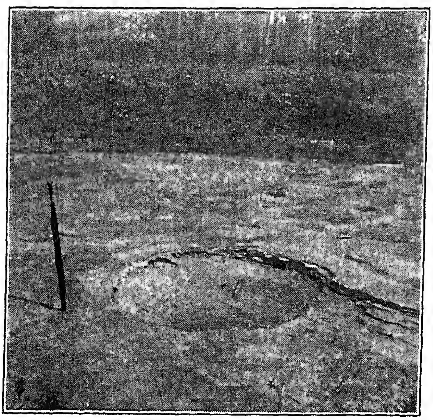


FIG. 583. — A small craterlet or funnel-shaped depression formed during the Charleston earthquake. The umbrella indicates the size.

Numerous craterlets of the type formed in Calabria and the New Madrid region were opened on the flat country, some of them, which were aligned along a fissure, being twenty feet in diameter. Water, mud, and sand gushed from these, in some cases to a height of twenty feet (Fig. 583).

Three railroads entering Charleston from different directions had their rails twisted, bent, and wrenched, especially where the fissures crossed the tracks. The number of killed and wounded was slight compared with other earthquakes. The shock of this disturbance was distinctly felt in Chicago, 800 miles away (Fig. 584).

The Sonora Earthquake of 1887

On May 3, 1887, a violent earthquake affected more than one half of Mexico and two thirds of New Mexico and Arizona, but

owing to the sparsely settled condition of the district, little damage was done to life and property. The region most affected was the old province of Sonora on the northern border of old Mexico. "Here a range of mountains, the Sierra Teras, was uplifted between faults which opened on either side" (Hobbs). The displacement varied from zero to 20 feet. In places along the western fault, the displacement was in the opposite direction.

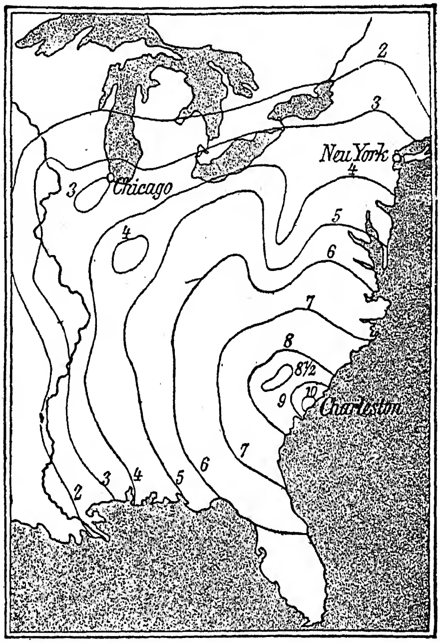


FIG. 584.—Map of the Charleston earthquake, showing the isoseismic curves formed by connecting the points in which the shocks were of equal magnitude. The order of shocks is: 1, microseismic; 2, extremely feeble; 3, very feeble; 4, feeble; 5, of moderate intensity; 6, fairly strong; 7, strong; 8, very strong; 9, extremely strong; 10, shock of extreme intensity.

"Millions of cubic feet of rock were thrown down from the slopes into the canyons and water courses, and cliffs of compact rock were shattered and split as though by a charge of giant powder" (Hobbs). Hundreds of small fissures, accompanied frequently by vertical displacements of one or two feet, opened in the flat country (Fig. 585), some of these discharging water, and numerous craterlets two feet or more in diameter opened along the fissure lines and gushed forth water and sand. All the water courses of the San Bernardino Valley experienced a change in level of from six inches to two feet. While much water gushed up and the streams became swollen during the shocks, the water dried away immediately after, the springs also going dry.

Numerous forest fires were started, probably by friction or by sparks struck from flint rocks during the land-slips.

Japanese Earthquakes of 1891 and 1896

Japan is probably one of the most unstable countries of the earth. During a period of nearly 1500 years, 225 destructive earthquakes have been recorded, and the careful records kept since the beginning of the seventeenth century show that a destructive earthquake has occurred somewhere in Japan about once in every two and a half years.

FIG. 585. — Small fissure and fault in the Arizona desert, formed during the Sonora earthquake of 1887. (After Branner.)

On October 28, 1891, occurred the greatest shock so far recorded in Japan. It affected an area of 243,000 square miles, or more than three fifths of the whole of Japan. The most violent manifestations were, however, largely confined to the provinces of Mino and Owari, which form a kettle-shaped basin covered by broad rice fields and surrounded by high mountains except on the south.

This region had been undisturbed for a long time, and the great shock came with unforeseen suddenness. Within a few moments 20,000 buildings were destroyed, 7000 persons were killed, and 17,000 more injured, many perishing by the fires which blazed up everywhere. The center of the district was fissured in an extraordinary way, and an open fissure a mile in length appeared on the banks of the Shonai River, where a bamboo grove "with pines and thatched houses was shifted *en bloc* 60 feet back from the river embankment, the trees remaining upright and the thatched roofs falling to the ground without fracture" (Hobbs). Small mud-volcanoes and sand craters arose in numbers all over the plain.

This earthquake was the accompaniment of a great fault which transected the valley in a general north-northwest and south-southeast direction. The part on the east of this line was lowered with reference to the other side and also was shifted along the

fault to the northwestward from three to six feet. In general, the vertical displacement was less than two feet, and there was no fault scarp, but a ridging of the ground resembling a gigantic mole track. In some places, however, as at Midori, there was a vertical displacement of not less than 18 feet, but in the opposite direction, with the formation of a great fault scarp. The lateral displacement in this case was in the same direction as elsewhere, and amounted to about 12 feet (Fig. 586).

FIG. 586. — View of the great fault produced by the earthquake of 1891 at Midori, in the Neo Valley, Japan. (After B. Koto.)

Many smaller displacements occurred along the rifts opened around Omori, some blocks rising, others sinking, as in the cases of the Owen's Valley earthquake of 1872. At one place a reservoir was cut in two by the fault, the northern half being depressed and shifted and the southern half drained. Two village sites were transformed by depression into a deep swamp two square kilometers in area.

During the five months succeeding this shock, no less than 2588 after-shocks were recorded, as many as 318 occurring on the day after (102 on the first day), gradually diminishing in number and intensity thereafter.

On August 31, 1896, a heavy earthquake affected the province of Northern Honshiu, killing, however, only about 1000 persons, since preliminary shocks from six to eight hours before had given the warning. A great magnetic disturbance occurred 33 hours before the great shock. A mountain range forms the backbone of Japan in this province (Fig. 587), and on opposite sides of this two great clefts, the Senya and Kawafune clefts, opened with the great shock. The latter cleft was accompanied by a vertical displacement of six feet. Where it crossed a crooked road near the village of Kawafune, it cut out, raised, and laterally displaced a section of it. A small house on the fault line was stood upon its head without further injury. The fault was traced for 15 kilometers, though not always showing displacement.

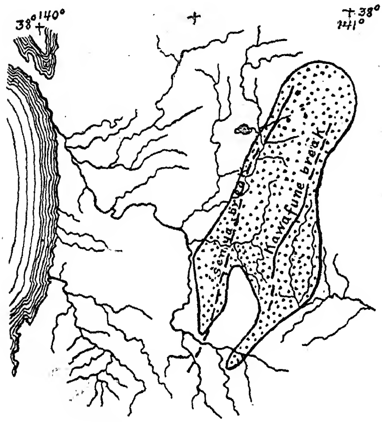


FIG. 587. — Map of part of the province of Northern Honshiu, Japan, showing the area affected by the earthquake of August, 1896. (After Yamasaki.)

The Senya cleft or fault on the opposite side of the mountain range was traced with some interruption for 60 kilometers, and it had a maximum vertical displacement of 10 feet. It appears to be the continuation of an older cleft farther to the southwest at Sakata, formed by the earthquake of 1894.

Icelandic Earthquake of 1896

A series of destructive earthquake shocks affected southwestern Iceland on August 26 and 27 and September 5, 6, and 10, 1896. The region affected is a triangular plateau bordered by lofty mountains, which include Mount Hecla and other volcanoes. These, however, were quiescent before, during, and after the earthquake.

Each of the five great shocks affected a different area or block of the region, though these were all contiguous. The blocks thus affected were outlined by great fissures upon the surface, and the succession of movements passed, in general, from the east westward.

The surfaces of the blocks were agitated so violently that neither men nor cattle could stand. Persons lying near a cliff were thrown over it, and in one village a heavy stove, six feet in height, was thrown a distance of twenty-five feet. Many fissures were opened, one of them extending for seven and another for nine miles in length. The mountains around the plain were fissured, and land-slips occurred on the steep bordering slopes. Many funnel-shaped openings were formed, and swamps and ponds in some cases were drained by them. A new hot spring arose after the shock of September 5, throwing water streams and volcanic rock to an estimated height of 600 feet. After a few hours, however, it rose only 10 or 12 feet in the air, and ten days later had entirely ceased to flow. The geysers of the region were also affected, one of them, the Strokr, which had come into existence during an earlier earthquake (1789), becoming suddenly extinct and remaining inactive since. (See p. 186.)

Assam (India) Earthquake of 1897

On June 12, 1897, a violent earthquake shook the district about Assam, India, laying in ruins a region 150,000 square miles in area within the period of fifteen seconds. The heavy shocks were all over in less than two and one half minutes, having shaken an area of 1,750,000 square miles.

A rumbling sound like thunder preceded the shocks by a second of time, increasing to intensity so as to drown the noise of falling heavy masonry near by. The ground rocked in waves "as though composed of soft jelly." Many monuments were twisted, and posts and houses were driven into the sandy ground, only the roofs of the houses remaining visible.

Numerous fissures, generally parallel to the mountain ranges, were opened, and some closed again as if under great pressure. Craterlets six or more feet in diameter appeared, and sand and water were thrown from these to heights of seven or eight feet or more. With the sand were fragments of peat, lignite, resin, half petrified pieces of timber, and a black earth not previously known from that district. Similar material issued from the cracks and was spread by the water over the surrounding country. The streams were temporarily swollen, the Brahmaputra advancing as a wall of water 10 feet in height.

The largest of the many displacements formed at this time was

the great Chedrang fault, which crossed and recrossed a meandering stream, closely following its general course for a distance of about 12 miles. The maximum displacement was 33 feet, but generally less. In some cases the fault was distributed over a series of parallel rifts, with shiftings of as much as several inches along these. In cutting the stream channel, the displacement caused the production of many ponds, lakes, and waterfalls. Readjustment in the hills resulted in many local changes in level, in amounts up to twelve feet, and changes in location of similar amounts as well.

After-shocks of lesser intensity followed the initial destructive shocks and continued for more than a week, but gradually faded away.

The Yakutat Bay (Alaska) Earthquake of 1899

A heavy earthquake occurred in southern Alaska in September, 1899, but little was known of it until the region was explored in detail in 1905. The country was broken into blocks, some being elevated, others depressed, the extent of such changes being frequently measurable on the fjords and other parts of the coast. In general, the changes of level ranged from 5 to 12 feet, but extreme changes up to 30 and even 47 feet were noted. Large blocks were broken into smaller ones, and these underwent individual adjustments.

New reefs and islands appeared as the result of this block adjustment, one of these being 450 feet long, about 75 feet broad, and apparently rising from deep water. In some places the sea has encroached on sunken forest lands, killing the trees; in others, raised beaches indicate elevation, several periods of elevation sometimes being shown.

The great wave or *tsunami* which accompanied this earthquake devastated a forest 40 feet above the level of the bay, the twisted and fallen trunks now lying in utter confusion. Great changes were also produced in the glaciers of the region.

California Earthquake of 1906

The great earthquake which partly destroyed San Francisco on April 18, 1906, is still fresh in the minds of the present generation. The heavy shocks came without warning at 5.12 A.M. They continued for about a minute and then graded off into lighter shocks, which were repeated during a period of several days. The

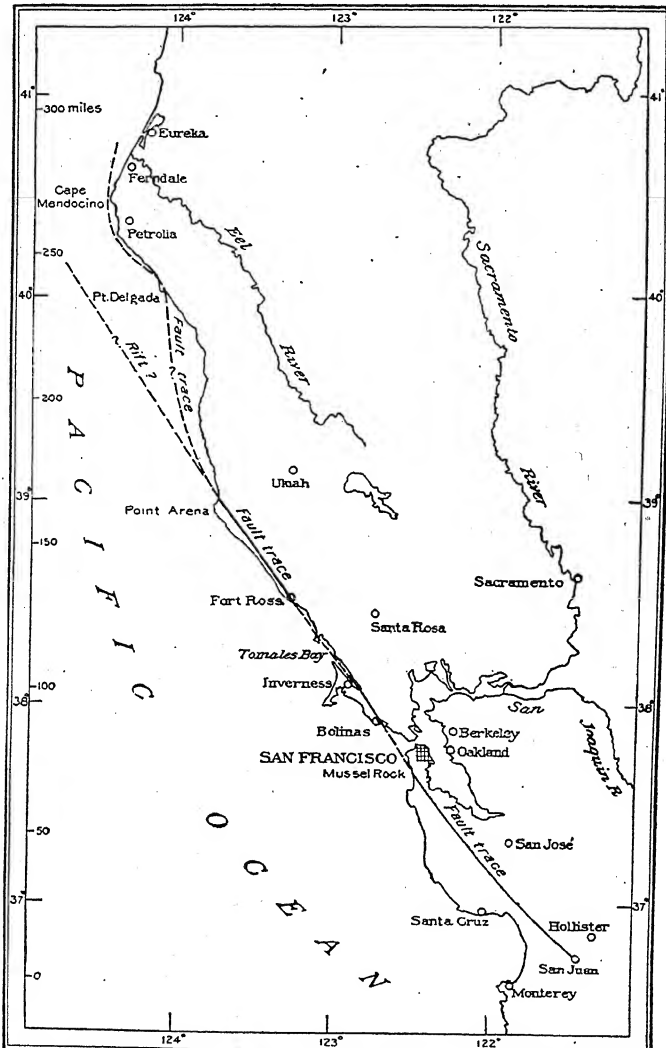


FIG. 588. — Map of the fault trace of the San Francisco earthquake of April 18, 1906. Broken lines indicate alternative hypothesis as to its extension north of Point Arena. (U. S. G. S.)

shocks accompanied movement along the Great Fault Line which runs, in general, parallel to the coast and is traced from Punta Arena on the north to the vicinity of Mount Pirnos in Ventura county on the south, a distance of about 400 miles, and with a general direction of N. 35° W. (Fig. 588). This is an old fault line, and repeated movements have occurred along it, all probably accompanied by earthquakes. In the latest earthquake, movements took place along this line for at least 185 miles, these movements being partly vertical and partly lateral displacements. On the southwest side of the fault, the shifting was generally to the northward, ranging from a few inches to 20 feet. A reverse displacement, however, occurred at Tomales Bay, north of San Francisco, where the offset in the opposite direction was about 20 feet. The southwestern side was usually also the uplift side, the amount being not over four feet. In some cases, however, an uplift of as much as two feet occurred on the eastern side.

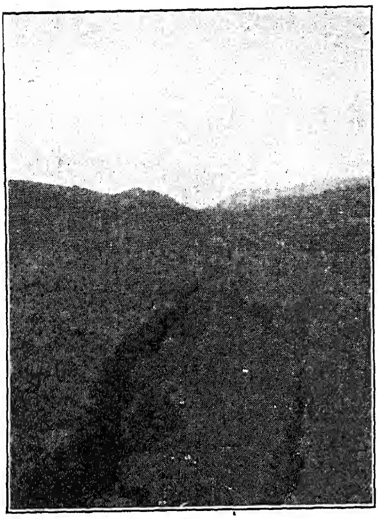


FIG. 589. — Earthquake fissure, associated with faulting. California earthquake. The main fault between Point Reyes Station and Olima looking southeast. The ground at the right of the fault has moved toward the observer; at the left, from the observer. (U. S. G. S.)

As no large cities are located upon the fault line, the amount of destruction along it was limited. The chief destruction was done along a line nearly parallel to the fault and northeast of it, where it is marked by the straight eastern shore of San Francisco Bay. On it are located the towns of Ukiah, Cloverdale, Healdsburg, and Santa Rosa in the north, and San Jose, south of Oakland, through which it passes. All of these towns suffered severely, especially the parts built on unconsolidated material, which was thrown into vibrations of greater amplitude than was the case with the solid rock. San Francisco lies between these two lines of faulting and over a subordinate fault line. The main destruction

wrought there by the earthquake itself extended roughly in a northeast-southwest line (along the direction of Market Street). When this line is extended, it roughly forms the straight northwestern coast of Suisun Bay, and there the railroad track sank in the marsh at the time of the earthquake.

This earthquake was accompanied by the usual phenomona of fissuring of the ground (Fig. 589), of lateral displacement of

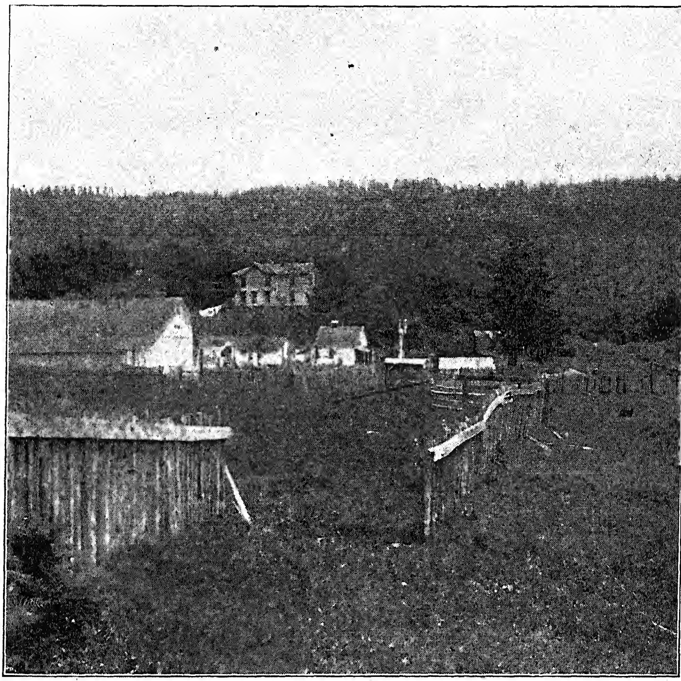


Fig. 590. — Fence displaced during the California earthquake of 1906. (Photo by G. K. Gilbert, from U. S. G. S.)

fences, roads, etc., to the extent of 10 feet (Fig. 590), the lateral shifting of the foundations underneath the buildings, the twisting of statues on their pedestals or their overthrow, etc.[1]

The loss of life was comparatively small, though perhaps 1000 persons perished. Much of the destruction in San Francisco was due to the fires, which could not be extinguished because the water pipes laid across the fault line were cut in two.

[1] For details see Bulletin 324, U. S. G. S., 1907; 170 pp., 57 plates.

The Jamaica Earthquake of 1907

The island of Jamaica in the Greater Antilles lies along lines of deformation which go back at least to Tertiary time, and has been repeatedly subjected to seismic disturbances. The city of Kingston seems to be a focal point from which the lines of chief disturbance radiate. The old town of Port Royal, situated across the harbor, at the end of a seven mile sand-spit, was destroyed by an earthquake in 1692, the ground settling and causing the submergence of a large part of the old city. This settling has recurred lately. A heavy shock, preceded by subterranean rumblings, occurred on January 14, 1907, about 3.30 P.M., and was followed about 20 seconds later by a second one. Within a period of 35 seconds the main destruction was completed, although eight after-shocks followed, between February 5 and June 14. The east-west walls of the buildings within the city suffered most damage. Destruction almost equal to that at Kingston was wrought at Bluff Bay on the north coast, and it appears that a line of disturbance (seismotectonic line) crosses eastern Jamaica between these points. Extended northward, this line passes through Santiago de Cuba, where the shocks were strongly felt. Other lines of this type intersect Jamaica westward from Kingston, where they converge. Along one of these lines the cable to the city of Colon was fractured, four miles out from Bull Bay.

The faulting produced at this time seems to have been confined to a zone around the river harbor. A series of parallel step faults was produced on the inner side of the sand-spit, descending progressively toward the shore, and making an aggregate displacement of not less than 24 feet. At the intersection of one of these faults with a railroad track the latter was deformed by a short, sharp kink. The fissures repeatedly opened and closed, ejecting water and sand, and a series of craterlets was formed on the bottom of some of them.

In one instance the harbor was increased in depth to the extent of 27 feet, while the western end of the peninsula on which Port Royal stands was submerged from 8 to 25 feet, so that only the tops of the palm trees and roofs of buildings project above the water level. The usual twisting of statues and other phenemona were manifested during this earthquake.

Summary of Phenomena Due to and Accompanying Earthquakes

Having now reviewed some of the more important earthquakes of historic time, we may summarize their characteristics and the accompanying phenomena. In the first place, it must be emphasized that although volcanic eruptions are commonly accompanied by earth tremors, the great earthquake disturbances are independent of such volcanisms and are due to the giving way of the earth's crust in places under heavy strains. Such giving way produces fissures, or opens previously formed fissures, and along these both vertical and horizontal displacements suddenly take place. Vertical movements are both up and downward, sometimes only one occurring, as in the case of the upward tilting of the block mountain in New Zealand; in others both movements occur. Along the same fault line differential vertical movements may be in opposite directions, so that in different places the same side of the fault may form the relatively raised or depressed portions. Again, block faulting, the dropping down or raising of circumscribed blocks, is not uncommon. Upon the surface, the topographical effect may be a single, or a series of step-like fault scarps, or a ridge resembling a gigantic mole track. In general, the height of the scarp is only

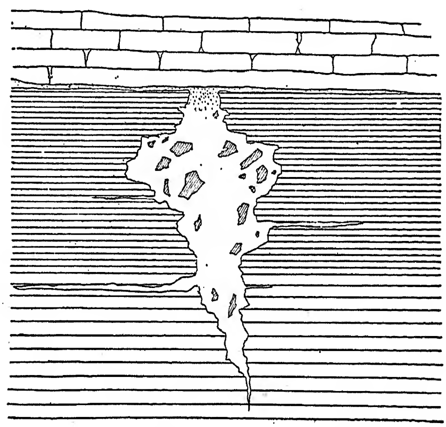


Fig. 591. — Diagram of an ancient fissure in fine Upper Silurian limestone, etc., filled with rounded grains of sand, secondarily enlarged, and including fragments of the wall-rock. The character of the fissure shows that it was formed suddenly and that the sand, which originally covered the surface, was violently injected, and sometimes driven into horizontal fissures between the strata. It is interpreted as an earthquake fissure, and the date of the earthquake is seen to have been sometime in Lower Devonian time, as the fissure is in Upper Silurian rocks, and the covering rock, which is unaffected, is of Middle Devonian age. Cement quarry, Buffalo, N. Y. For detail of included fragment, see Fig. 592, and for enlarged sand grains from the injected mass, see Fig. 472, p. 565.

a few feet, though displacements of as much as 47 feet have been recorded. Beneath the sea, however, much greater fault scarps have come into existence. Thus the earthquake of October 26, 1873, caused the cable to break seven miles from the cable office at Zante, Greece, by the formation of a submarine fault scarp 600 feet in height, the change in depth being from 1400 to 2000 feet. Other fault scarps 1000 feet in height have been formed in this region, and in one case a difference in depth of 2000 feet has been found between the bow and stern of the cable repair ship.

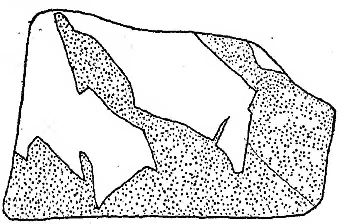


FIG. 592. — Fragment of the wall rock (limestone) included in an ancient sandstone dike; the rock is shattered and the sand (shaded) injected into the fissures. Somewhat reduced. Sandstone dike. Buffalo, N. Y. (For character of sand grains, see Fig. 472, p. 565.)

By the repeated opening and closing of fissures, sands from the surface, together with other objects, are injected into them, and thus sandstone dikes are formed, penetrating the rocks of the region. There are many ancient examples of such sandstone dikes (Figs. 591, 592). Another superficial effect produced upon the rocks is their shattering and the dislodgment of huge masses which are often precipitated to some distance.

When the surface consists of unconsolidated material, great earth waves are produced, which cause a rocking of structures, a bending back and forth of trees, and a rifting of the surface, with the spouting forth of sand and water and the formation of craterlets and mud-volcanoes. Huge landslides are also produced, and great masses of soil with trees and buildings may be shifted bodily. Subsidences also occur by a settling of the soil, and thus lakes, ponds, and submerged areas along the coast result. The damage to buildings on such unconsolidated bottoms is often much greater than to those built on rock.

Earthquakes originating near or under the sea produce great water-waves or *tsunamis*. These may rise 40 feet or more, and travel with enormous velocities and over distances of many thousands of miles. Recorded velocities range from 370 to 465 miles per hour, or from six to seven and three fourths miles per minute.

SLOW CHANGES IN LEVELS, BRADYSEISMS

In addition to the rapid modification of the earth's surface, described as accompanied by earthquakes, there are gradual changes in elevation which are not associated with detectable earthquake movements. These are often of great geological importance, especially when they produce depressions into which the sea may enter. We have already discussed the formation of geosynclines of deposition, and have seen that these imply slow sinking with simultaneous deposition of sediment, the aggregate of the slow subsidence amounting in the end to many thousands of feet. The actuality of such subsidences can be deduced only indirectly from the nature and extent of the sediment deposited in the subsiding area, and indeed actual observation of all slow earth movements, or *bradyseisms*, as they are called, is out of the question. There are, however, other evidences than the sediments to indicate slow changes in level, both upward and downward movements, and these may be found not only upon the sea-coast, but in certain cases inland as well. We will take three illustrations of such changes, one from the Temple of Jupiter Serapis at Pozzuoli, Italy, another from the raised beaches of the Atlantic coast, and the third from the changes of level observed in the region of the Great North American Lakes.

The Temple of Jupiter Serapis at Pozzuoli

The coastal district of Naples is of interest, not only because of the varied manifestations of volcanic activities, but also because of the unequivocal evidence of elevation and subsidence since the beginning of the Christian Era which is afforded by such monuments of antiquity as the ruined temple of Jupiter Serapis at Pozzuoli. (See map, Fig. 51, p. 110.) It is true that there is other evidence of change of level in this region, but none that is quite so convincing as that furnished by these ruins.

This temple (Fig. 593), built some centuries before the opening of the Christian Era, was of circular form, 70 feet in diameter, surrounded by a quadrangular court, and the roof was supported by 46 noble columns, of which 24 were of granite and the rest of marble. Only three of the marble pillars remain erect, each carved out of a single block, their height being 40 feet 3½ inches. One is nearly bisected by a horizontal fissure, the others are entire,

and they are all out of the perpendicular, inclining slightly to the sea. For a height of about 12 feet above their pedestals, the surface of the pillars is smooth and uninjured. Above this is a zone about nine feet in height, where the marble has been pierced by the boring mollusk, *Lithodomus*, many shells of which still exist in the pear-shaped inward-enlarging hollows. In some of these borings, shells of another marine mollusk (*Arca*) also occur. These holes clearly indicate that at the time of their formation the parts of the columns thus affected were beneath sea-level, and their depth and size is such as to suggest that this state of submergence lasted for a considerable time. The fact that the lower part of the pillars is unaffected, indicates that at that time this part was protected by sediments or otherwise. The amount of submergence is marked by the height of the bored zone, the upper parts of the pillars projecting above water-level. Marble columns lying on the pavement of the temple were also attacked by borers, while worm-tubes (*Serpulæ*) became attached to them.

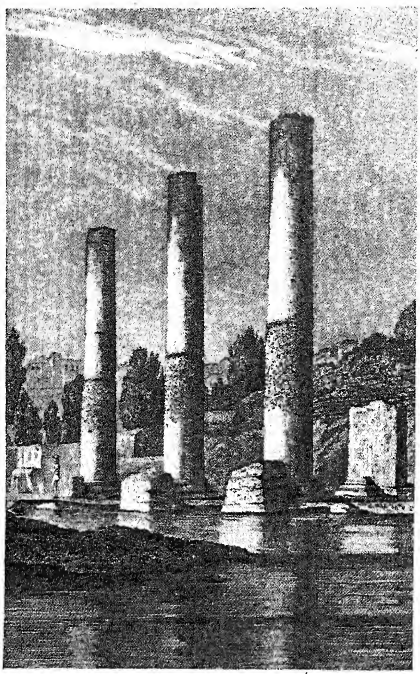


FIG. 593. — Ruins of the temple of Jupiter Serapis at Pozzuoli as they appeared in 1840, with the floor partly submerged. (After Lyell.)

At the time of Lyell's visit in 1828, the platform was about a foot under water, — the sea, only 100 feet distant, soaking through the intervening soil. The top of the bored zone was, therefore, at least 23 feet above high-water mark, the tides in the Bay of Naples being small. An older, costly mosaic pavement was found by excavation about 5 feet below the upper one, indicating subsidence before the building of the later temple floor. That the

temple was intact, and stood above water-level between the years 222 and 235 A.D. is clearly attested by historical evidence, and, therefore, the great subsidence occurred much more recently. That it antedated the close of the fifteenth century is shown by a description of an Italian writer dated 1580, in which he said that 50 years before, or in 1530, the sea washed the base of the hills which rise behind the flat land on which the remains of the temple stand, and "a person might then have fished from the site of those ruins which are now called the stadium," and which stand upon these hills.

A series of deposits around the lower part of the pillars and the outer walls of the temple, record the changes in history and show that the subsidence was gradual. "The sea first entered the court or atrium and mingled its waters partially with those of the hot springs [which still exist]. From this brackish medium a dark calcareous precipitate was thrown down, which became, in the course of time, more than two feet thick, including some serpulæ in it. The presence of these annelids teaches us that the water was salt or brackish. After this period the temple was filled up with an irregular mass of volcanic tuff, probably derived from an eruption of the neighboring crater of the Solfatara, to the height of from five to nine feet above the pavement. Over this again a purely fresh-water deposit of carbonate of lime accumulated with an irregular bottom (because of the uneven surface of the tuff)." The surface of this fresh-water deposit was level, and upon it followed another deposit of volcanic ashes and rubbish. Then came the subsidence, which permitted the boring of the submerged part of the pillars not protected by these deposits. Later showers of ashes buried the pillars in places to a height of 35 feet above the pavement, from which they were exhumed in recent times.

Certain historic evidence shows that the upward movement had begun before 1530, but the main elevation appears to have occurred at the time of the great eruption of Monte Nuovo in 1538, when, as we have seen (p. 112), the region thereabout was elevated.

Since the rediscovery of the temple in 1749, when it stood higher than now, it has undergone a renewed subsidence. At the beginning of the nineteenth century the floor was above sea-level, but in 1838 fish were caught every day over parts of the pavement, the conditions being as shown in the illustration published in 1840 (Fig. 593). Between 1822 and 1838 the rate of subsidence was

about one inch in four years, in 1847 it was about one inch a year, and in 1852 it had practically ceased. In 1857–58 the floor of the temple was covered by about two feet of water at high tide, on calm days. At the present time the surface of the pavement is slightly below sea-level.

Evidences are not wanting that these changes of level affected the whole of the Bay of Naples, and represent warpings of considerable areal extent instead of being a local phenomenon connected with volcanism, as has been supposed by some.

Raised Beaches

Scandinavia. — On the coast of Norway raised sea-beaches are found, which are held to indicate a movement in recent times to a height of 600 feet or more, although this interpretation has been questioned. It is a noteworthy fact, however, that these terraces, or beaches, are not only found in fjords, where they might have been formed on lakes dammed by ice, but that they also face the open sea, and occur even upon some of the islands. These raised beaches are both of the wave-built type of shingle beach and the wave-cut terrace type. On the Swedish coast, measurements of the rate of elevation have been made on monuments especially planted for this purpose. In one place, the rate of elevation was found to be about two feet per century, but it is not everywhere uniform, and varies from period to period.

Scotland. — Around the Scottish coast, such beaches occur at levels of 25, 50, and 100 feet above the sea, indicating step-like elevation. The higher beaches date back to the glacial period, as is shown by their organic contents and their association with boulder clay, but the lowest one is very recent, containing in many cases the shells of the Mollusca still living upon that coast (especially limpets) and incorporated in the modern beach. The lower two beaches can be traced nearly around Scotland, but the upper one occurs only in certain places.

Eastern North America. — In the coastal region of Maine, New Brunswick, and other districts, beds of clay are associated with beaches and sand-spits, and cliffs are cut into the glacial deposits, these cliffs being at present found at an elevation of about 300 to 600 feet above the sea-level. In these sands and clays are found the shells of cold-water mollusks (*Saxicava arctica*, Fig. 594, *Leda*, etc.), which are still living upon the coast. As the beaches

are partly cut into the glacial deposits at those elevations, it is clear that the region has been relatively raised some time after the formation of these deposits or, in other words, in comparatively modern times.

There are many other examples known which demonstrate recent changes in level along the coast, but those cited are so clear that they admit of no other explanation. Evidences of subsidence, such as the drowned Valley of the Hudson and other rivers, the

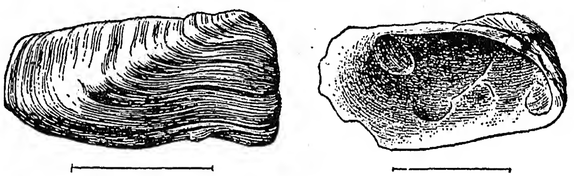


FIG. 594. — Shells of a pelecypod (*Saxicava arctica*) found in the elevated sand beds of northeastern New England, New Brunswick, etc. This species still lives in the modern ocean.

submergence of fresh-water peat deposits, of former forests, etc., also occur, but they are in some cases explicable in other ways. Enough has been said, however, to show that changes of level have occurred in recent times. Some of these, no doubt, were due to a change in the position of the sea-level, caused in part by the attraction of the great ice mass which covered the northern Atlantic regions, as already outlined (p. 297). Others, however, can only be regarded as representative of a change in the altitude of the land itself.[1]

Change of Level in the Great Lakes Region

The evidence of change of level in the region of the Great Lakes of North America is of an interesting and peculiar type. On the northeastern side of the Lakes, the old beaches are raised above the present water-level, in some cases to a height of several hundred feet. Followed southward and westward, these beaches descend toward the lake level and finally pass under it. This indicates a tilting of the lake-basins toward the southwest, and in support of this hypothesis, it is found that the water of Lake Michigan at Chicago rises at the rate of about 9 inches a century. At

[1] For further discussion of this problem see D. W. Johnson, "Shore Processes and Shore Line Development." John Wiley and Sons.

this rate it is estimated that the permanent discharge of the Great Lakes will be by this route to the Mississippi in 3000 years from now.

The tilting of the lake basin is explained by the rising of the old Ontario dome on the northeast, a dome which has repeatedly risen since Palæozoic time, with intervening periods of rest. The present rate of rise is estimated to be several inches in a hundred miles per century.

CHAPTER XXII

THE SCULPTURING OF THE EARTH'S SURFACE

Initial Character of the Land Surface

Plains. — The simplest form of land surface upon which the agents of erosion perform their sculpturing process is the *plain*. By this name is designated the surface of a country which over extensive areas shows very little relief. Indeed, some plains appear to the eye almost as level as the surface of the ocean. The rivers of the plain have as a rule shallow valleys and are for the most part sluggish, frequently with swampy or boggy borders.

Young Plains. — The most typical plains are plains of construction and are formed of horizontal or nearly horizontal strata upon which little erosion has been performed. Such plains are called *young plains*, and they may be divided into *coastal plains* and *inland plains*. A typical coastal plain borders the sea-coast, and represents portions of the sea-bottom which have been elevated but recently, so that erosion has made little progress, or elevated to such a slight extent that the work of the rivers and other agents of erosion has been unable to accomplish much dissection. Such a coastal plain borders the sea in southern New Jersey, and extends inland for many miles. It has a deep, sandy soil, and is generally overgrown with pine forests; its roads and railroads run in straight lines for long distances, and its population is scanty because of the infertility of the soil and the sluggishness of the streams and the consequent lack of water-power.

Inland plains may be formed by the deposition of strata of sand and clay either in old lake basins or by the confluence of river flood plains, as in the case of the Indo-Gangetic plain of northern India, (p. 468); the great alluvial plain of the Hoang-Ho of China (p. 467), and others of this type; or they may represent the flat till-covered surfaces left during former glaciation by the continental ice-sheet which once occupied that region.

Extensive plains may also be formed by wide-spreading lava flows, but these are seldom absolutely level. Plains always stand

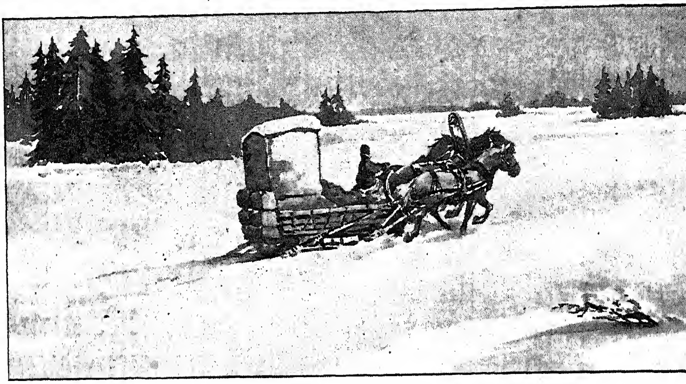


Fig. 595. — Winter scene on the plains of North Asia, showing the broad and level expanse of a young plain.

at a moderate altitude above the sea or other level which controls erosion, so that the rivers do not cut down deeply beneath the surface. The great plain of western Siberia, in latitude 50° to

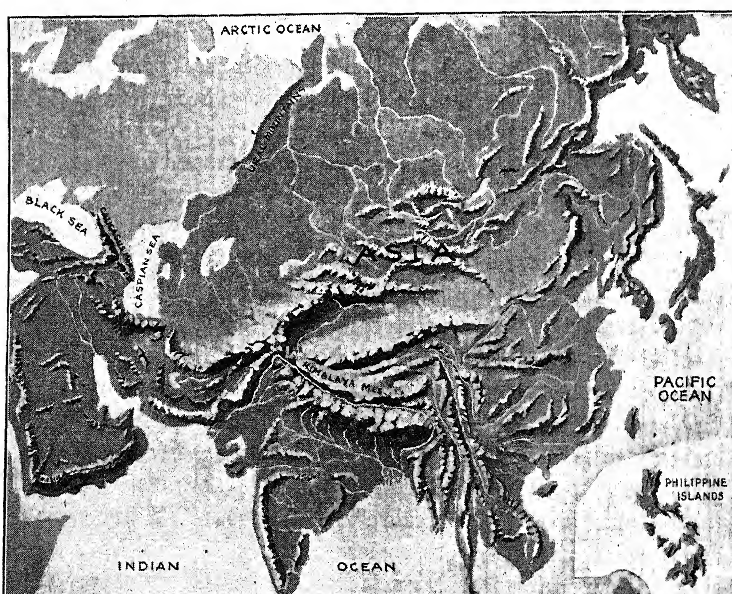


Fig. 596. — Relief map of Asia.

60° N., is not greatly elevated above sea-level and preserves an even surface over hundreds of miles. "Vast areas, stretching further than the eye can reach, are monotonous in the extreme, almost as uniform in soil as in surface. The flat areas between the streams, having no distinct lines of water parting and no distinct channels of water discharge, are as yet practically undivided among the rivers. Marshes, alternately wet and dry in winter and summer, and many shallow lakes lie in faint depressions, as if slight

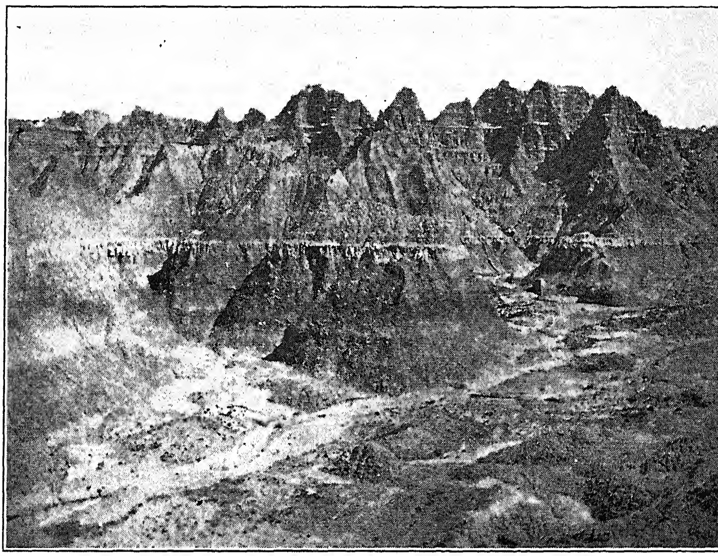


FIG. 597. — Badlands of the Great Plains, showing horizontal plains structure. South side of White River, three miles below Porcupine Creek. (U. S. G. S.; courtesy of D. W. Johnson.)

inequalities in the original surface of the plain had not yet been drained by river action. The valleys are few and far between; they can never be cut deep while the region stands low. They are narrow; hence the rivers have as yet worked only for a comparatively short time in the earth's history. The plains are still young." (Davis.) (Fig. 595. See also relief map of Asia, Fig. 596.)

Mature Plains. — When a plain has been thoroughly dissected by streams and by the work of the atmosphere, especially the wind, so that its topography presents the maximum of ruggedness which it can acquire under the existing conditions, it is said to be *mature*. Such thoroughly dissected plains are also spoken of as

"Bad Lands," because of the difficulty of traversing them (Fig. 597). The same plane may be maturely dissected in one part, while in another the original evenness of surface may show but little modification.

Old Plains (Erosion plains). — A plain which has been produced as the result of prolonged erosion of a region, until that has been worn down again to a level surface, — that is, a plain of denudation, — is spoken of as an old plain. The great plain of central Russia is one of the largest examples of such a plain of erosion, and

FIG. 598. — Relief map of Europe.

it might at first sight be mistaken for a young plain, it is so level and monotonous over vast areas. The rocks underlying it do not, however, correspond with the surface, although they are nearly horizontal. They are mostly firm and consolidated, instead of loose sands, etc., as in young plains, and the surface is not formed by the same stratum as is the case in young plains, but bevels across the layers at a very gentle angle. Thus from place to place different layers are exposed, with the result that slight changes in the form of the surface and the soil, resulting from the decomposition of the strata, are produced. The rivers flow in

narrow channels of moderate depth, indicating that little erosion has been accomplished since the formation of the plain. It is customary to designate such an erosion surface by the term *plane* (Fig. 598).

The Peneplane.[1] — An old plane of erosion is also designated a *peneplane*, because it is seldom a perfect plane, but generally "almost a plane," as a peninsula is almost an island. The great Russian peneplane above referred to is an example of such a sur-

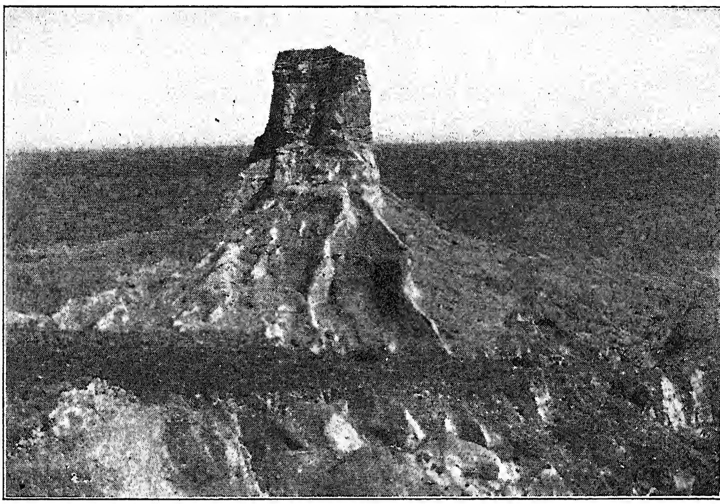


Fig. 599. — Jail Rock, Cheyenne County, Nebraska. A butte of sandstone capping clay, rising as a monadnock above the peneplaned adjacent portions of the Great Plains. (Photo by Darton, U. S. G. S.; courtesy of D. W. Johnson.)

face of moderate elevation; but most peneplanes have been uplifted again, and are undergoing renewed dissection. The Great Plains of western North America represent such an erosion surface on nearly horizontal strata, and they appear to the eye as absolutely level or gently rolling surfaces, as shown in the preceding illustration, where only a small remnant of erosion, "the Jail Rock," rises above the very level plane, representing one of a number of remnants of the former higher surface (Fig. 599). This surface is, however, undergoing renewed dissection in other regions. The Prairie Plains of the central United States represent a broadly

[1] It has become customary to use the terms *plane* and *peneplane* for surfaces of erosion, restricting the term *plain* to surfaces of construction of low relief and horizontal strata.

peneplaned surface which still stands at a moderate altitude above the sea (from 500 to 1000 ft.) and is therefore subject only to slight dissection. Much of this area is covered by the till or ground moraine left by the great ice sheets which buried this region in Pleistocene time, while other parts are covered by the river and loess deposits, derived from the ice-borne material. These newest sediments mantle over the peneplane surface, and thus in reality convert it into a constructional or true plain. It

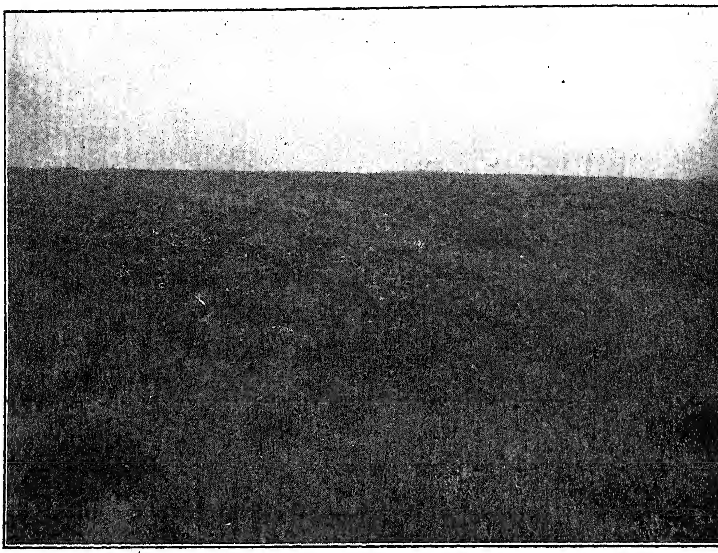


FIG. 600. — The untamed prairie. The broad monotonous expanse of these plains is due to the peneplanation of the underlying rock and the veneering of the surface with glacial, alluvial, eolian and loess deposits.

is this mantling by glacial débris which gives the surface of the prairie its level, monotonous character (Fig. 600).

While many peneplanes are cut on nearly horizontal strata, there are others which have been cut on complexly folded rocks. The New England peneplane is of this type, and so is that which cuts the old, much-folded slate mountains of western Germany, in which the Rhine has sunk its beautiful gorge (Fig. 601). It is evident that such a peneplane, cutting across strata of varying hardness, must represent the lowest level to which streams could erode at the time this erosion surface was formed, this in the examples cited being approximately sea-level. From the fact that the

modern streams have again cut gorges and valleys below this level we must conclude that the peneplane has been elevated, with reference to the sea-level, since its formation.

Plateaus. — A typical plateau, like a typical plain, is composed of horizontal strata, but its surface stands at a much greater elevation above the floors of the valleys which transect it, than does that of the plain. A young plateau presents a wide, level surface, with few but deep and narrow cañons cut in it, which form its most pronounced feature, since the upland surface itself, because of its even, monotonous character, attracts little attention.

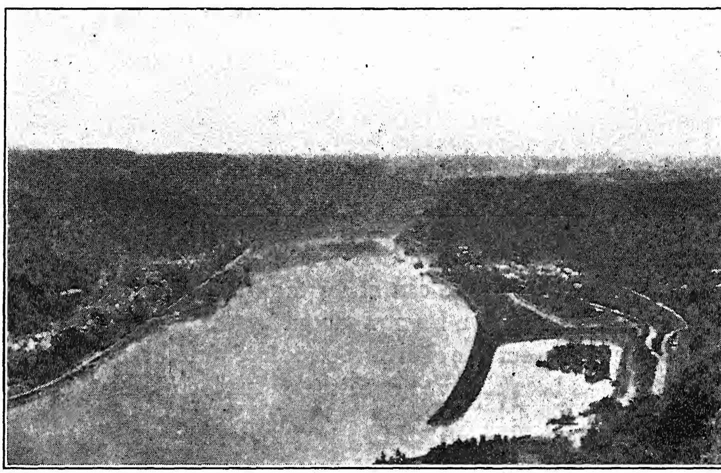


FIG. 601. — Gorge of the Rhine at St. Goar, Germany. The gorge is seen to be incised in an older valley, remnants of the floor of which are seen somewhat below the remarkably even skyline of the peneplane. (Photo by D. W. Johnson.)

Many so-called plateaus are really uplifted peneplanes cut on horizontal strata, as in the case of the Alleghany Plateau of the eastern United States. Some of the little dissected plateaus of the western states are, however, regarded as young plateaus in which erosion has progressed only to a slight extent. In the rivers dissecting young plateaus, as well as in those which dissect uplifted peneplanes, waterfalls often form a characteristic feature. Another marked feature of many recently uplifted plateaus is the broken and flexed character of their strata, so that recent fault scarps and monoclinal flexures diversify the surface. Such modifications of the surface character are clearly shown in the Colorado

Plateau of Arizona and southern Utah represented in the diagram (Fig. 619 *b*).

Deformed Surfaces. — Many initial surfaces are far from being level but are more or less strongly deformed. Such deformed surfaces are found on fault blocks, dome mountains and anticlines. Besides these there are minor constructional surfaces, such as volcanic cones, drumlins, etc., which present inclined surfaces and offer special opportunities for the sculpturing processes.

The Erosion Cycle in the Sculpturing of the Land Surface

The surface features of the earth are largely the result of the sculpturing processes which are constantly and everywhere at work, and the details of operation of which we have studied in previous chapters. But it must be clearly understood that the nature of the rock and its attitude, — that is, the structural features of the earth's crust, — exercise an important controlling influence upon the sculpturing processes, and that it is only by taking those features into account that we can understand the bewildering series of land forms which have been produced by the agents of erosion or sculpture upon a surface of diverse structure and history. Hence this subject has been reserved until the discussion of such features had been completed.

The Cycle. — We shall first discuss the general progress of surface sculpture from the beginning to the end, that is, to the obliteration of the surface features produced during the process. For, unlike a human sculptor, nature is not content to produce finished land forms from the earth-block she is working on, but must needs continue, after the sculpture is finished, to reduce its salient features, and keep up the process until the originally produced complex form has been again destroyed and the block brought back nearly to the relative simplicity of form which it had at the beginning of the process. It is as if the sculptor, having produced his bas-relief upon a stone front, were to continue his carving and cutting, gradually removing the salient features until all resemblance to the work produced originally is lost, and the surface of the stone again becomes plain and without relief features.

This process of earth sculpture from formless surfaces to complex bas-relief, and on to formless surface again, constitutes the

cycle of erosion, and the agents which accomplish this cycle are the familiar ones of the weather, that is, the gases and vapors of the atmosphere, the wind, rain, frost, and diurnal and seasonal temperature changes; and also the streams and the glaciers, and the waves and currents upon the coast.

Stages of Relief. — In the beginning, when the diversity of relief is slight, the surface is said to be in the stage of *youth*. As dissection progresses, the bas-relief reaches its maximum complexity and diversity of form, when the condition of *maturity* is approached, beyond which it passes on to *old age*, which is reached when the surface is again reduced to a condition of little or no relief. The last stage, in which the surface would be a perfect plane, is seldom if ever reached, for as it is approached the agents of erosion work more and more slowly, and before its final accomplishment the unstable nature of the earth's crust may effect a change of conditions and a new cycle of sculpture or erosion become inaugurated. Such an unfinished surface, the end stage of an incomplete cycle, is presented by the *peneplane*.

Monadnocks. — The unreduced relief features which rise above the peneplane, and which are the residual remnants of the former diverse relief, are called *monadnocks*, from the mountain of that name in New Hampshire, which was first recognized as representing such a residual relief feature upon a peneplane to which we shall refer again later on (Fig. 635, p. 742). Jail Rock, shown in Fig. 599, is such a monadnock, rising above the peneplane surface of the Great Plains.

Relation of Peneplane to Base-level of Erosion. — Since the materials removed by the natural agencies of land-sculpture are carried away by agents acting under the influence of gravitation, it is evident that the sculpturing processes may continue until the surface of the country subjected to them is lowered to the level, which for the time being, limits the force of gravitational control. This downward limiting surface is called the *base-level of erosion*, and in most regions this is the level of the sea, for beneath this level, few of the agents of erosion may cut to any great extent. Therefore, we may assume that sea-level is the ultimate base-level of erosion, and that in a prolonged cycle the surface of the land as it approaches the peneplane condition also approaches the level of the sea. This level will of course not be reached by the peneplane the rivers of which are tributary to the sea, except at its

margin, for the surface which is undergoing subaërial erosion must always have a certain amount of slope, in order that the material removed from it may be carried away. A peneplane which faces the sea may, however, be planed down by the waves from the margins inward, thus producing a *plane of marine erosion*, or marine peneplane.

Fig. 602. — Intrenched meanders in San Juan cañon, Utah. The course of the river is antecedent and superimposed, for it was developed before the surface attained its present altitude, and is independent of the structure of the rocks. The meandering course was probably established when the river was flowing on a graded plain and became permanent when by elevation the stream was reinvigorated and cut into the rising rock surface. (Photo, copyright by H. H. Vinson. By permission Yale University Press, from *Military Geology and Topography*, edited by Herbert E. Gregory.)

Local Base-levels.—There are, however, local base-levels of erosion which are independent of the level of the sea. The floor of the Sahara Desert lies in part at least beneath the level of the sea, and so does the surface of the Caspian Sea (Lake). Both of these deeper levels control the extent to which erosion of the bordering lands can be carried, and erosion surfaces formed about their margins will be lowered until they approach these deeper levels. In the great interior deserts, such as those of Tibet and other Asiatic regions, the base-level of erosion, which is the desert floor, lies thousands of feet above

the sea-level. Nevertheless, for the time being it controls the level to which erosion of the surrounding country may progress. Where the local base-level of erosion in an arid region is an enclosed dry basin which receives the sediment from the surrounding regions, this base-level will gradually rise as the basin is filled with the wastage of the surrounding hills, and so the ruggedness of the district will be partly reduced by filling or *aggrading*, and partly by down-cutting or *degrading*. In this manner a complex high-level plane, partly of erosion and partly of local filling by sediments, will come into existence. Such a plain is, of course, produced only where the hollows formed by wind erosion are filled by sediments washed into them, and this can take place only in a region which is not absolutely rainless.

The Inauguration of the New Cycle. — When the peneplane is raised with reference to the sea-level, or where by a change in conditions the base-level of erosion controlling an interior peneplane is lowered, a second cycle of erosion begins. The streams once more will incise their courses into the surface, until they again approach a condition of grade, that is, have such a relation to the new base-level of erosion that their cutting power has practically ceased. As the streams upon a peneplane generally assume a *meandering course*, winding about over the surface to follow the easiest path, they will upon elevation of the peneplane maintain this course, and so large rivers of a region in the second or later cycles of erosion will present the phenomenon of *intrenched meanders* (Fig. 602). Such intrenched meanders may also present the phenomenon of a cut-off, leaving an intrenched oxbow, as at Lauffen on the Neckar River in Württemburg (Fig. 603). Lateral tributary streams will gradually dissect the elevated upland. Finally, as the second cycle approaches completion, the region will again assume the character of a peneplane.

Relative Ages of the Rivers and of the Land

There is no relation between the topographic age of the land surface and that of the river dissecting it. It is true that in newly emerged coastal plains, young rivers are a characteristic feature, but previously existing rivers will also flow across such a coastal plain from the old land bordering it, and while the part entering the coastal plain will at first have the characters of a youthful stream, its greater volume of water will soon produce a valley that

has all the characteristics of maturity. In like manner, young rivers may come into existence on an old land surface, such as a peneplane, by uplift of this surface, while the older streams upon such a surface will become rejuvenated and assume the characteristics of a youthful stream.

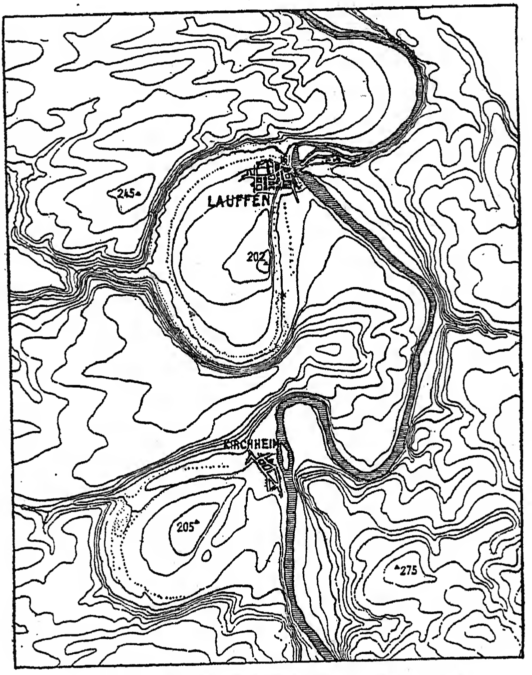


FIG. 603. — Intrenched meander cut-off of the Neckar River at Lauffen and at Kirchheim. The cut-off portions are occupied by small streams. The cut-off at Lauffen is the most recent, the form of the old valley still being clearly marked. At Kirchheim the river has cut below the level of the old cut-off. (From de Martonne.)

A young stream is characterized by a narrow valley or gorge with steep sides, and with little or no flood-plain surface on the valley floor, which is occupied for the most part by the stream. The gorge of Niagara and that of the Genesee at Portage present such youthful conditions, and these are also seen in the Colorado River, and in fact in all rivers which run in narrow cañons which they are still actively eroding; such rivers are frequently characterized by waterfalls. A mature river, on the other hand, has

widened its valley by lateral cutting, and built a flood-plain upon its floor, which it no longer completely fills. On this flood-plain it will meander, cutting away portions at one place (the concave bank), and building at another (the convex bank) (Fig. 604). Such continued erosion results frequently in the cutting off of the larger meanders, leaving them as "oxbows" still occupied by water, as in the case of Lakes Chicot and Lee and others in the Mississippi Valley (Fig. 605), or as dry oxbow valleys. Such

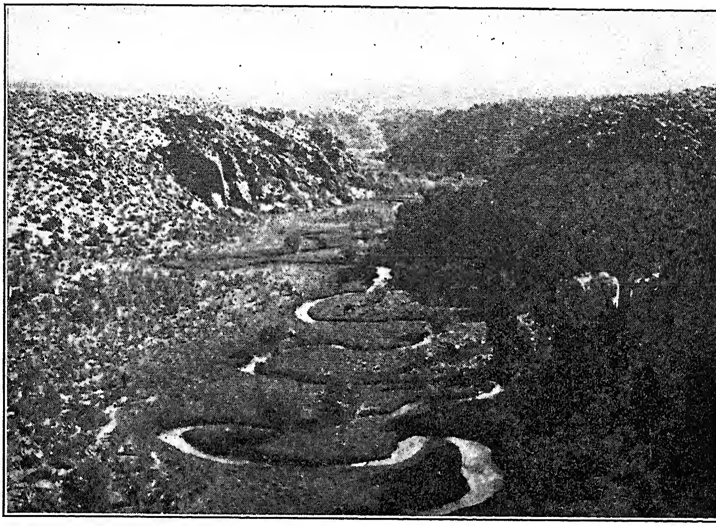


Fig. 604. — Crooked Creek, near Long Valley dam site, California. Meanders of stream on flat floor of a mature valley whose sides are unusually steep in certain localities where hard rock ledges project into the valley. (U. S. G. S.)

cutting-off shortens the river, often by many miles, and increases its velocity along the new course. The manner of their formation has been discussed in a previous chapter (p. 417).

The Erosion-Cycle on a Simple Coastal Plain

Characters of the Coastal Plain. — A coastal plain such as that which faces the Atlantic from New Jersey to the Gulf, with a width varying from a few miles to over a hundred miles, represents an emerged strip of former sea-bottom. The sediments of which it is composed represent the deposit formed in the littoral district of the sea when it covered this region, and the shore-line of which

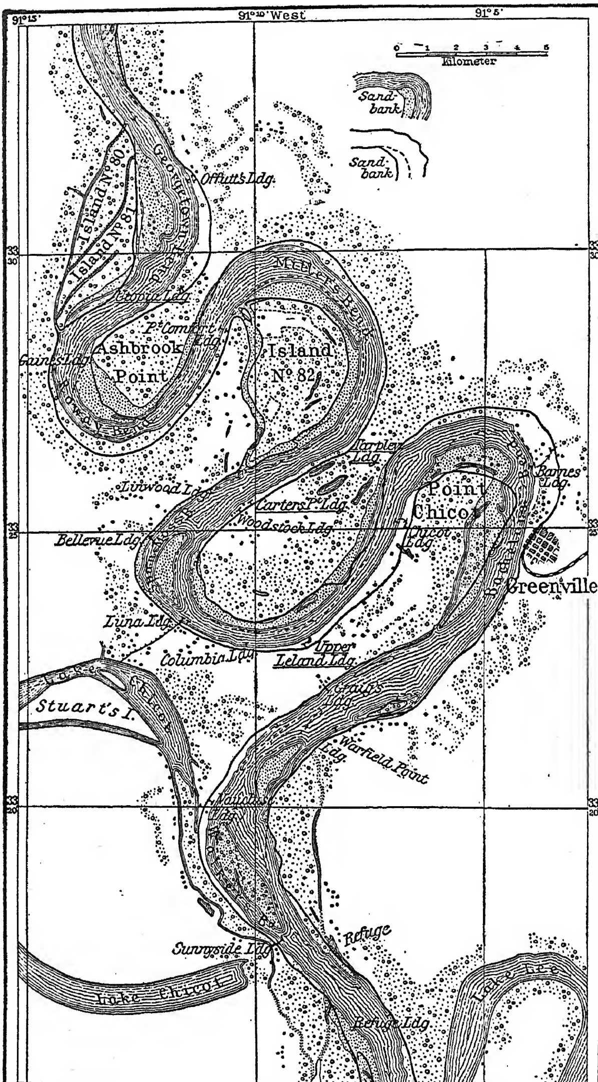


FIG. 605.—The meanders and oxbows of the Mississippi. (Miss. River Comm., 1881–82 and 1894; from Ratzel.) Lakes Chicot and Lee represent cut-off portions of the river, now forming oxbow-lakes. The portion shaded by waterlining represents the river bed according to the surveys of 1881–82, the sandbanks of that period being dotted. The black line represents the bed of the river according to the survey of 1894, and the sandbanks of that period are outlined by dotted lines. The new landing-places erected since 1882 are underlined.

lay approximately along the inner margin of the present coastal plain. Not all coastal plains are composed of simple marine deposits; indeed, the example cited contains delta and alluvial deposits which were formed above sea-level, these being especially characteristic of the lower part of the series. Nor is the marine series always continuous, but, as in the example cited, it is more often the product of successive encroachments and withdrawals of the sea. Nevertheless, this series may be treated as a unit, and in our discussion of erosion we may assume simplicity of structure as typical of such a coastal plain.

Although appearing horizontal, the strata of the coastal plain are in reality gently inclined seaward, finally passing beneath the

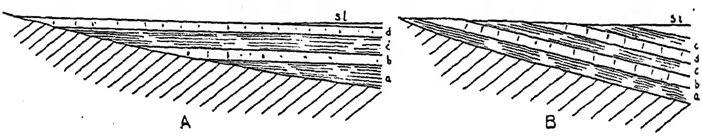


FIG. 606. — *A*. Diagrammatic section of coastal plain strata in a transgressive or overlapping series. *B*. A similar series formed in a retreating sea (off-lapping series). *a* and *c* are soft strata, *b* and *d* are hard strata. The strata are represented as of the same character throughout, though in reality they change in lithic character toward the shore.

level of the sea. This may be in conformity with the slope of the surface, or it may be somewhat in excess of that, depending upon whether we are dealing with a transgressive series of strata suddenly emerged, or with a retreatal one, the product of slow emergence. The two types are shown here in section (Fig. 606, *A*, *B*).

For the sake of simplicity we shall consider the transgressive series only, and we shall further assume that this series consists of alternating deposits of hard and soft strata. The former may consist of sands bound together by calcareous material (*b*, *d*), the latter of muds, etc. (*a*, *c*) (Fig. 606, *A*).

Drainage Systems of the Simple Coastal Plain. — Upon a simple coastal plain, where the surface is comparatively uniform and regular, sloping gently to the sea, a definite type of drainage will develop. The rain-water run-off (see p. 411) will flow down the slope to the sea, soon forming for itself definite lines of drainage, which, following the shortest course, will in general be at right angles to the coast. Such streams, the first to be formed, are called *consequent streams*. Streams which were in existence on

the oldland when the coastal plain had not yet emerged will, if persisting, become extended across the coastal plain to the sea. These are the *extended consequent* streams, and since they originate in the mountains or higher oldland, they will generally have more water than the newly formed consequents upon the coastal plain, and so be able to cut deep and wide channels more quickly than these. Such larger streams are spoken of as the *master consequents*.

Along the margin of the consequent streams others will come into existence from the near-by run-off, which finds its shortest course into the consequent. These streams are not consequent on either the initial slope of the surface, or difference of rock resistance sufficiently pronounced to be recognizable. Hence they are spoken of as inconsequent, or, more briefly, *insequent* streams. They cut back their channels from the edge of the consequent valley and prolong their own valleys by headward cutting.

If the coastal plain structure is of the simple type above outlined, with its strata progressively overlapping upon the oldland, and if the capping stratum is of uniform character throughout, the drainage pattern developed will consist of the two types of streams so far described, namely, the consequents and the insequents. The former cut downwards, the latter headwards, increasing in length and complexity until a complicated drainage system of the multiple-branching type is produced.

It is, however, conceivable that near the inner end of the coastal plain the conditions may be such that the insequent streams developed there may have an advantage over those formed farther down on the coastal plain. If the oldland is abrupt and high, the moisture-bearing winds, on striking them, may be forced to rise and part with some of their burden of water, and many of the mountain streams thus formed may find their way into, or be gathered up by, the growing insequents, as these prolong their valleys by headward cutting. In this way a portion of the inner edge of the coastal plain may be removed, the oldland being stripped of its cover of coastal plain strata.

Coastal plains are, however, seldom, if ever, as simple as here outlined. As we have seen, they are often composed of strata due to repeated advances and retreats of the sea, with the result that the inner edge of the coastal plain differs considerably from

that of the simple type first described. Moreover, the strata of a coastal plain are never uniform throughout, but, as has been shown in a previous chapter, their lithic character changes as we approach the shore of the sea in which they were formed. All of these characters combined may render the inner edge of the coastal plain less resistant to erosion, and as a result, a new type of stream, the *subsequent*, will develop, which differs from the insequent in that it develops by headward erosion along this belt of weaker rocks. If the coastal plain consists primarily of a series of strata deposited in a retreating sea, the ends of the weaker strata will be exposed, as shown in diagram *B*, Fig. 606, and along the weaker strata subsequent streams will develop. Again, if weaker strata are exposed because of the peneplanation of a coastal plain series, subsequent streams will develop along these exposures; but these belong to a later cycle of erosion.

By the erosion of the inner edge of the coastal plain, the valley of the subsequent stream is produced, and this, in a general way, will be at right angles to the valley of the consequent. Erosion in this region progresses with relative rapidity because of the weaker character of the strata upon which it takes place, and thus, partly by the wearing activities of the stream, and partly by that of rain water and the rapid weathering of the softer rock, the valley of the subsequent will be broadened until it becomes wide enough to be termed a lowland. As this lowland lies next to the oldland, or on the inside of the coastal plain, it is called an *inner lowland*. It consists in part of a *stripped belt*, where the coastal plain strata have been removed down to the rock of the oldland, and in part it is cut from the coastal plain strata. (Compare Figs. 607 *a* and *b*.)

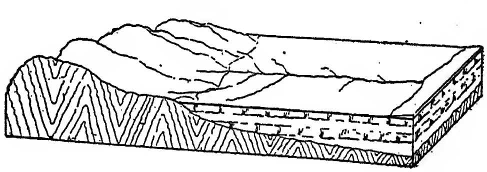


FIG. 607 *a*. — Diagram illustrating the coastal plain of overlapping strata, with consequent and insequent drainage.

The inner lowland will be bordered on one side by the sloping surface of the oldland, and on the other, the seaward side, by the eroded edge of the coastal plain. If the top stratum of this coastal plain is of resistant rock, a cliff will crown this cut edge, especially if the cutting has been deep enough to expose

the softer bed just beneath. In this manner the coastal plain will end landwards in a steeper slope or *inface*, and between this inface and the oldland lies the *inner lowland* (see Fig. 607 *b*). The remnant of the coastal plain thus separated from the oldland is called a *cuesta* (pronounced *kwesta*), and this topographic feature is characteristic of the mature stage of dissection of the coastal plain. Two types of streams thus are necessary to produce the cuesta: the consequent which flows down the dip of the strata, and the subsequent which flows along the strike of the strata.

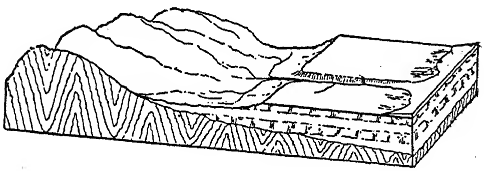


FIG. 607 *b*. — The same region shown in Fig. 607 *a*, after the development of subsequent streams and the formation of an inner lowland. The remnant of the coastal plain now forms a cuesta ending landward in an inface, and transected by the consequent stream valley.

The inface of the cuesta may also become the site of development of a fourth type of stream which flows down it and into the subsequent stream which occupies the inner lowland. These streams likewise increase in length by headward erosion, and as they flow in the opposite direction from that of the original consequent, they have been called *obsequent streams*. They form the third side of a rectangular drainage pattern thus established. By their activities, portions of the front of the cuesta may become separated from the main part and constitute plateau- or butte-like outliers — or table mountains, if high. These are characteristic features of many cuesta fronts. (See Fig. 633, p. 740.)

It must always be borne in mind that the depth of the inner lowland, which is occupied by the subsequent streams, cannot be greater than the depth of the consequent stream valley to which these subsequents are tributary, and that it is the master stream of the region which determines the maximum depth to which erosion of all the valleys may proceed. The present Atlantic coastal plain of eastern North America appears to be in essentially this state of dissection, although parts of it have suffered great modifications. In the southern part of the plain, the normal cuesta topography is easily recognizable. Thus in Alabama we find next to the oldland which is formed by the subdued mountains of the Appa-

lachians, the Black Prairie Valley, which forms the inner lowland, and the name of which is derived from the dark color of the rich soil, weathered from the underlying weak limestone. This flat inner lowland includes the best cotton district of the state, and in it lie the cities of Montgomery and Selma. Proceeding seaward we note the rising ground of the inface of the cuesta, locally called the Chunnemugga Ridge, which is rather abrupt, though not characterized by steep cliffs, and upheld by a more resistant limestone stratum. Numerous small obsequent streams run down this inface of the cuesta and dissect it. At the top of this inface, which rises 200 feet above the inner lowland, the Hill Prairies and Pinelands

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Fig. 608. — The "Pine-Barrens" — on the southern part of the Atlantic Coastal Plain of the United States.

begin, and the cuesta surface falls with an imperceptible slope to the sea (Fig. 608). The Alabama, Tombigbee and Chattahoochee rivers are the chief consequent streams rising in the oldland and traversing the cuesta to the sea.

Farther north, in Maryland, Delaware, and New Jersey, the coastal plain has suffered depression after the erosion topography was produced. As a result the sea has entered the river valleys and produced shallow inlets or bays, of which Chesapeake and Delaware bays are conspicuous examples, though marine erosion has greatly modified and widened these original river valleys (Fig. 629, p. 738). Still farther north, the drowning of the coastal plain has been so complete that it allowed the sea to enter the inner lowland. In this manner Long Island Sound was

produced between the inface of the cuesta which forms the northern shore of Long Island (here modified by the superposition upon it of the terminal moraine of the ice age) and the Connecticut shore, which is a part of the oldland. Much of the seaward side of the old coastal plain has also been submerged, this accounting in part for the narrowness of the remaining portion which forms Long Island.

Completion of Cycle of Erosion; Formation of the Peneplane. — As erosion continues, the inface of the cuesta is pushed farther seaward and the inner lowland is widened. If a second hard layer is discovered during the progress of erosion, the inface will assume a terraced condition, each hard layer forming a cliff, and the softer

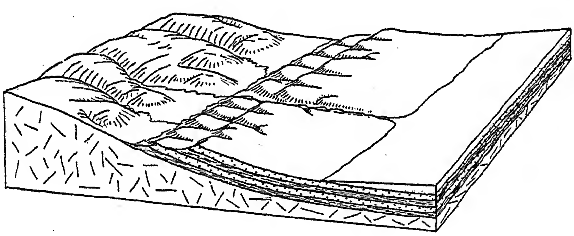


FIG. 609 *a*. — A coastal plain in the first cycle of erosion. The presence of two hard layers produces a terraced cuesta front. In exceptional cases the upper terrace may weather back with sufficient rapidity to constitute a second cuesta with a lowland of some width between it and the lower cuesta, if the weak stratum between the harder is of sufficient thickness. (Drawn by Mary Welleck.)

one between, a slope. Continued erosion will eventually result in the complete destruction of the cuesta and the formation of a peneplane. As the surface of this peneplane will have a gentler slope than that of the strata composing it, it is evident that this surface and the strata will intersect at a moderate angle, with the result that the outcropping ends of the strata are beveled across by the erosion plane. This is shown in the following diagrams (Figs. 609 *a*, *b*), the first of which (*a*) shows the terraced cuesta of two hard layers, while the second (*b*) shows the completion of the peneplane and the beveling across of the strata. If the coastal plain consists of a retreatal series of strata (Fig. 606 *B*) each weak stratum will form a lowland and each hard one a cuesta.

It will be observed that, as the result of this beveling, the outcrops of the strata are in the form of broad belts, and that, in con-

sequence, the outcrops of the two hard layers *b* and *d* are separated by a broad belt of soft strata.

Across such a peneplane the original consequent streams will continue to flow, but because of the disappearance of the original bounding walls of these streams, they are no longer confined to a straight course, but may begin to wind or meander, partly because

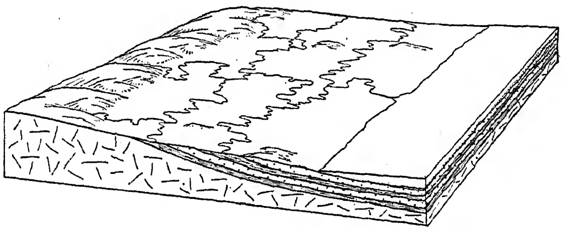


FIG. 609 *b*. — The same region shown in Fig. 609 *a*, after peneplanation. The strata are now beveled across by the peneplain, and the rivers are no longer controlled by the topography. (Drawn by Mary Welleck.)

of obstructions left by the diminished current in dropping its load of sediment, and partly for other reasons; and as the outcrops of the harder beds are more and more reduced to the general level of the peneplane, they will come to have less and less influence upon the course of the streams.

Beginning of the Second Cycle of Erosion. — If, after the region has been reduced to the condition of a peneplane, it suffers a re-

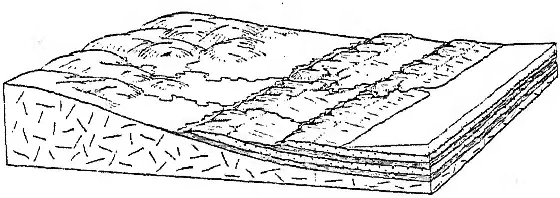


FIG. 609 *c*. — The same district shown in the two preceding diagrams, after elevation and renewed dissection. Two cuestas and two lowlands are now produced from the hard and weak strata, respectively. (Drawn by Mary Welleck.)

newed bodily elevation, the streams will be rejuvenated because their slope is increased, and they will once more begin to cut downwards. Here again the consequent streams, especially those which flow from the oldland to the sea, will determine the rate and extent of downward cutting, for all other streams are tributary to these consequents, and cannot cut below the level attained by them.

If the consequent streams have begun to meander upon the surface of the peneplane, they are apt to retain that meandering course, and the new channel or gorge which they cut during the second cycle will be characterized by incised or *intrenched meanders*, the existence of which is generally suggestive of a second or later cycle of erosion (Fig. 610). (See also Figs. 602, p. 706, and 603, p. 708.)

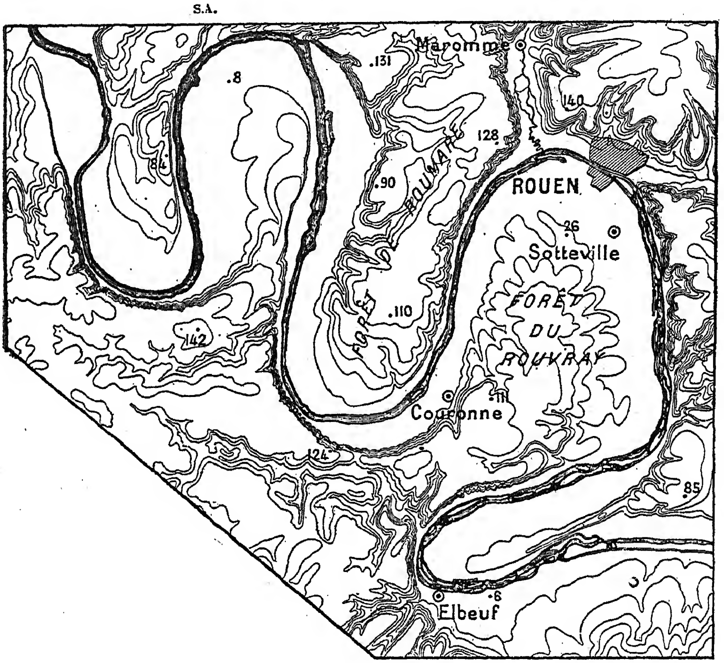


FIG. 610. — Intrenched meanders of the Seine in the old peneplane cut upon the strata of the Paris Basin; near Rouen. (After de Martonne.)

As the consequent streams cut their transverse channels across the outcropping belts of the soft and the hard layers alike, the lateral streams will also begin cutting, but they will be largely confined to the softer belts which are more easily eroded. As a result, subsequent valleys will be formed upon these softer belts, and the harder ones will gradually be modeled in relief as new ridges, and eventually each will assume the appearance of a cuesta inface, fronting a lowland cut upon the soft belt. But there will now be two such cuesta infaces and two broad lowland valleys, one the inner lowland between the oldland and the inface formed by the

lower hard stratum, the other between this latter and the inface formed by the upper hard stratum. The diagram (Fig. 609 *c*) illustrates the result thus produced.

These two cuesta ridges may now be many miles apart, but their summit elevation will be in the same plane, as they formed part of the original peneplane surface. They may, indeed, retain a part of the beveling which was produced during the peneplanation, as is indicated in the diagram.

Central England as an Illustration. (Fig. 611.) — What is generally regarded as a good illustration of such a belted structure with two cuestas and lowlands, is seen in the topography of central England. If we consider the rugged hills and mountains of Wales

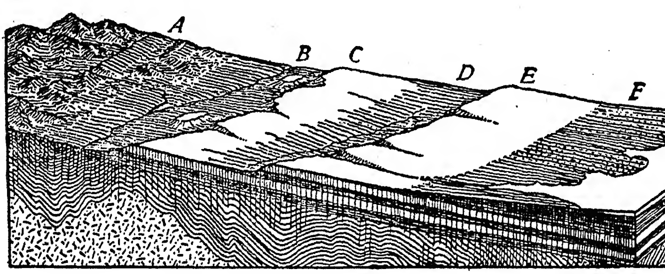


FIG. 611. — Block diagram of the cuestas and lowlands of Central England. *A*, Oldland of Wales; *B*, Inner lowland (Triassic); *C*, Oölite cuesta, Cotswold Hills; *D*, Outer lowland (Green-sands and Gault); *E*, Chalk cuesta, Chiltern Hills; *F*, London coastal lowland. (After Davis.)

as a part of the oldland (*A*) we find to the east and southeast of this a broad inner lowland cut upon soft red sandstones and marls (Triassic). In this lowland (*B*) are situated the cities of Bristol, Nottingham, and York. Rising from this lowland belt upon the east is the first ridge or cuesta (*C*), which extends in a curving line across central England from southwest to northeast, and is formed by the edges of the lower hard limestone strata (Oölites) which overlie the red sandstones. Near Bristol this upland belt forms the Cotswold Hills, and it is characterized by a relatively steep westward and very gentle eastward slope. Next east of this lies the second lowland (*D*), cut upon the second belt of soft strata (Gault and Green-sands) and in this are situated the cities of Cambridge and Oxford. A second upland or cuesta (*E*), bounds the eastern and northeastern border of this lowland, this being formed by the resistant chalk. It constitutes the Chiltern

Hills on the south, and from the summit of the cuesta there is a gentle slope toward the London coastal lowland (*F*).

While this illustrates in a general way the double cuesta type of topography produced in a second erosion cycle, there are many local modifications, owing to the disturbances of the strata by folds and faults, and the history of the region is on the whole more complex than here outlined.

River Capture in Coastal Plain Dissection. — It has been shown that in every coastal plain undergoing dissection there is apt to be a master consequent stream which, because of its greater water supply, cuts deeper and more rapidly than the other consequent streams. The tributaries to such a stream have the advantage over the tributaries to another consequent, in that they are enabled

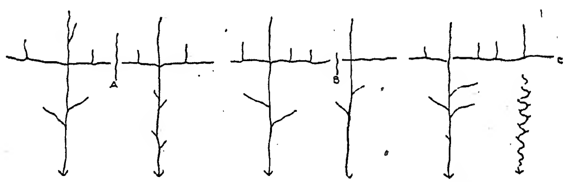


FIG. 612. — Diagrams showing the progress of river capture and beheading. At first the divide is halfway between the two consequent streams at *A*; but the subsequent tributary of the stronger consequent encroaches upon the territory of the weaker one, pushing the divide to *B*; continuing, it beheads the weaker stream, capturing and diverting its headwaters (*C*). The beheaded stream now follows a wriggling course in its old valley, which becomes much obstructed by the débris from the sides which this stream is no longer able to carry away.

to cut deeper and tend more rapidly to extend their territory by headward cutting. Of two subsequent streams flowing in opposite directions into separate consequents, the one tributary to the master will have the steeper slope, and so be enabled to extend its drainage territory at the expense of the other subsequent, which is progressively robbed by the more powerful stream. Thus while the divide between the two tributaries (subsequents) may at first have been at *A* (Fig. 612), it has gradually been pushed to *B*, and finally, at *C*, tapped the headwater portion of the smaller consequent, making it a captured tributary to the master stream. The beheaded portion of the smaller consequent will remain as a much diminished stream in its original valley. Since the lateral insequent streams continue to bring in at least the same amount of sediment as before, this must now be partly dropped upon

the floor of the valley occupied by the beheaded consequent, because this river is no longer able, on account of its diminished water supply, to carry this material away. Because of the obstructions thus produced, the diminished stream of the valley must frequently change its course. To the extreme irregular windings thus assumed, the name "staggering course" is applied, and such a course may in general be said to be characteristic of recently beheaded streams.

Meanwhile the area appropriated by the master stream will be deepened in conformity with the depth of that stream, and so the inner lowland floor may be cut far below the level at which the beheaded consequent continues to flow, the valley of this stream ending abruptly against the much deeper subsequent valley. This is illustrated in the following diagram (Fig. 613), and may be re-

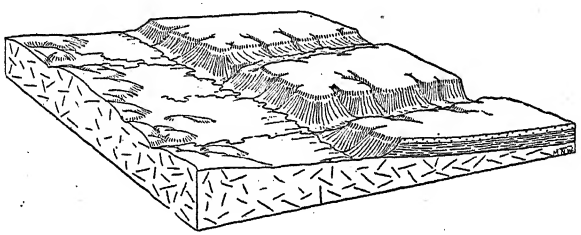


Fig. 613. — Overdeepened subsequent. (Drawn by Mary Welleck.)

garded as a characteristic feature of the valleys of beheaded streams on dissected coastal plains. Such conditions may develop during the first, and during any later cycle of erosion, and as a result the form of the drainage system of the master stream, after it has captured a number of streams, will resemble that of a well-trained grape vine.

Waterfalls in the Coastal Plain Drainage System. — Large waterfalls are not a characteristic feature of the coastal plain proper, though small ones are formed in all the streams which flow over hard strata of the coastal plain deposits. Along the head of the coastal plain, where the extended consequents and other streams pass from the oldland of hard rocks to the lowland cut on the soft belt of the coastal plain, a series of waterfalls is likely to come into existence, for the hard rocks of the oldland permit less rapid erosion than do the softer rocks of the valley adjoining. The inner border of the coastal plain thus becomes a

"fall line," and it is here that water power is developed, which favors the location of large cities and towns. Trenton, Philadelphia, Washington, Richmond, Raleigh, Camden, Augusta, and Columbus are all located upon the fall line of the Atlantic coastal plain where it is crossed by large rivers.

The Erosion Cycle on Domes and Basins

The Black Hills Type

The Black Hills of South Dakota represent an uplift of the strata in the form of a very regular dome of oval outline 100 miles long north and south and 50 miles broad east and west. The strata on the flanks are raised to angles of 45 degrees or more, and the original height of the dome was about 5000 feet above the surrounding plain. The normal erosion cycle upon such a dome proceeds somewhat as follows.

Radial Consequents. — The first type of stream to come into existence on a newly raised dome of this kind is a series of radial consequent streams which flow down the sides of the dome in all directions. At the base of the dome they become tributary to one or more streams which carry away the drainage, but these have no especial significance in the development of the drainage topography of the dome. As the strata are removed from the summit of the dome by erosion they gradually begin to form a series of rimming outcrop belts around the center, the highest or youngest stratum forming the outermost, and the oldest the innermost belt. Wherever a hard bed of sandstone or limestone alternates with softer shaley or marly beds, a ridge will be formed from the hard bed, which, because of the steep inclination of the strata, will have a triangular section, the outer slope being formed by the surface of the hard stratum and the inner by the cut edges of the series. Such a uniclinal ridge is called a "hog-back" (Fig. 631, p. 739), and the Black Hills are encircled by a number of such hog-backs concentrically placed around the central region. Between the hog-backs are circling valleys cut upon the softer strata, and one of these, cut on red shales and soft sandstones, has such a regular form that the Indians called it the "race course." Because of the red color of the rock it is also known as the Red Valley. The drainage of these valleys is carried through a series

of water gaps in the hog-backs or uniclines, and these gaps form the avenues of approach to the central mountainous area.

This central area is formed by the old crystalline rocks, here raised high above the surrounding country and largely stripped of their former covering of sediments. They have been dissected into a series of peaks and ridges, which to-day rise to 2000 or 3000 feet above the plain and which by forcing the winds to rise compel precipitation. They are therefore clothed with dark forests (hence the name Black Hills), and they form a marked contrast to the more arid rolling treeless plains which surround the hills. The presence of precious metals in these ancient rocks has made this a center of active mining operations. The following cross-section shows the position of the hog-back-forming strata and their former extent across the dome (Fig. 614).

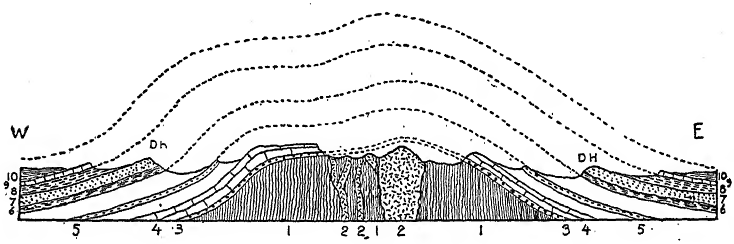


FIG. 614. — Cross-section of the Black Hills dome, showing the present structure and topography and the former continuation of the beds. 1, Archæan slates and schists; 2, granite; 3, basal Cambrian sandstone; 4, limestone (Ordovician at base, Carbonic for the most part); 5, Red beds shales and sandstones (Triassic) forming the Red Valley; 6, Jurassic shales, etc.; 7, Dakota sandstones; 8, Cretaceous shales; 9, Cretaceous limestone; 10, Tertiary strata; *DH*, Dakota hog-back.

Flat Domes

Ozark Plateau. — The Ozark Plateau of Missouri represents a low, flat, but somewhat asymmetrical dome of great extent, steeper in the south, and which has been dissected so that the strata which once covered it are now found chiefly as rimming belts around the flanks. Only a small area of the underlying crystalline rocks is exposed in the St. Francis Mountains in the northeastern part of the dome. Over the greater part of the Missouri area, the Cambro-Ordovician strata, which immediately overlie the crystallines, form the surface rock of the so-called Salem upland. These are dolomitic limestones and sandstones, dipping at such low angles that they appear horizontal. They are dis-

sected by streams which in general have a radial arrangement, partly with reference to the St. Francis Mountain area, but chiefly with reference to the geographic center of the dome. Some of the valleys cut by these streams are 250 feet or more in depth (Fig. 615).

The northern slope of the dome is characterized by a succession of broad, flat plateaus, separated by escarpments of irregular outline formed by the harder strata, which here dip northward at a very low angle, so that the escarpments have the characteristic appearance of cuesta fronts. They are partly formed by Silurian and partly by Mississippian limestones. Many outliers are found in front of the escarpments and mark the progress of differential retreat. The western and southwestern margins of the dome are formed by the Springfield Plain, which faces the center of the dome in the Burlington escarpment and is another cuesta-like structural feature. It is produced by the harder Mississippian limestones which dip gently to the west in Missouri and to the southwest in Arkansas, the slope of the surface of the plain corresponding to the dip of the strata. Outliers also characterize the front of this escarpment.

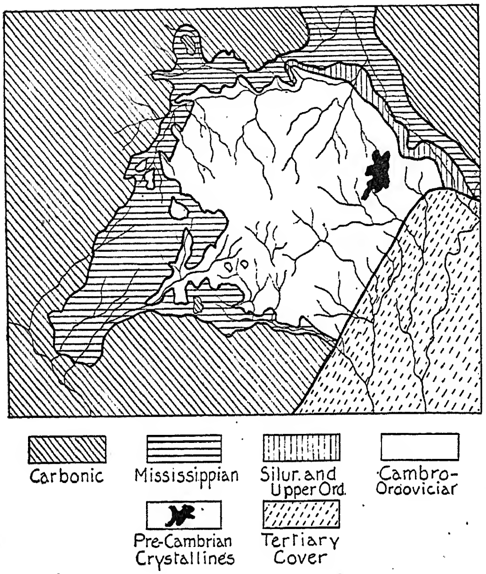


FIG. 615. — Geological map of the Ozark dome, showing the concentric arrangement of the outcropping formations and the radial drainage.

On the south, the margin of the dome is formed by the continuation of the Burlington escarpment, and farther away by the Boston Mountains, the rocks of which dip southward at a somewhat greater angle than do those of other portions of the dome. The front of this ridge is a bold escarpment capped by a resistant layer of sandstone, and from it many finger-like prolongations extend

northward, while dissociated remnants form outliers to the north of the main escarpment. The topography becomes rougher toward the east, where the plateau and escarpment characters are obscured. On the southeast the dome passes beneath the alluvial lands of the Mississippi River.

This dome differs from the Black Hills Dome in that its rimming elements have a cuesta-like character, owing to the nearly horizontal attitude of the strata, whereas the steeply inclined strata of the Black Hills Dome form rimming hog-backs. Like the Black Hills case, however, the strata which now end in escarpments on the north, west, and south, formerly extended across the Ozark dome, and have since been removed from the central part by erosion.

Ontario Dome. — A less perfectly preserved low dome of the Ozark type is seen in the Ontario region north and east of the Great Lakes. Over the greater part of this dome only the old crystalline rocks are now exposed, but around its eastern, southern, and southwestern border, and in part on its northwestern as well, the sedimentary strata which once covered it to a large extent, if not completely, are still visible, forming a series of more or less rimming escarpments which face the center of this dome. As is the case with all the domes of eastern North America, this one is not in its first cycle of dissection, but has been at least once reduced to the condition of a peneplane since the end of the Palæozoic, when its main elevation took place. As a result, the strata which dip from 5 to 15 feet per mile are beveled across at a low angle and their outcrops form broad belts upon the surface. After the peneplanation a renewed upward movement of the dome took place in early Tertiary times, and this revived the radial consequent drainage. Many of the valleys of these revived radial consequents are still recognizable, though some have been deepened by glacial erosion and transformed into lakes, while others are filled by drift, or are partly occupied by streams which flow in the opposite direction. Of the over-deepened valleys, those occupied by the "Finger Lakes" of New York are typical examples. Their striking radial arrangement is the direct result of their origin as radial consequents, and a series of lines passed through them and marking the former courses of the rivers would converge somewhere near the center of the dome north of Lake Ontario (Fig. 616). The waters of these rivers, then flowing

southward, were gathered by the various branches of the Susquehanna and carried to the Atlantic. The continuity of these old valleys to their junction with the old valley of the Susquehanna can still be traced, and so can others, like that of the Genesee, now occupied by northward flowing rivers. Where not modified by ice erosion, these valleys are often from one to several miles in width, with gently sloping sides and flat bottoms, mostly covered to some depth, by sands and clays of later origin.

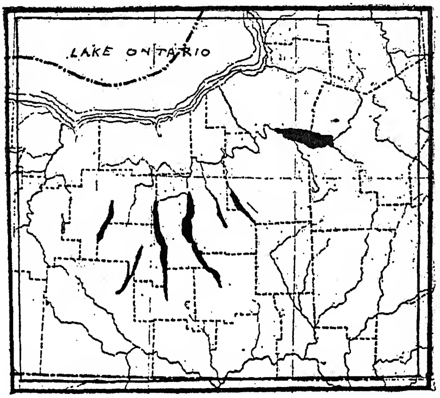


FIG. 616.—Map of a portion of central New York, showing the radial arrangement of the Finger Lakes.

The master stream valley of the region is now entirely filled in by glacial drift, but has been traced by borings. It passed through the western end of Lake Ontario, where, near the city of Hamilton, it was about three miles wide and of great depth. Its general direction of flow was to the southwest (Figs. 617, 618). Another of the radial consequent valleys can be partly traced through the gap in the ridge, which separates Georgian Bay from Lake Huron, and its southwestern continuation was apparently in the submerged valley which now forms Saginaw Bay. The waters of these streams were gathered and carried to the Mississippi by paths as yet only partially known.

In the later cycle of erosion the outcrops of the softer beds of this peneplaned dome were eroded into lowlands, and the harder beds formed new rimming cuestas. One of these lowlands is occupied by Lake Ontario on the south and by Georgian Bay on the west of the dome, the connecting portion being filled by glacial drift. Along the southern border of Lake Ontario extends the Niagara escarpment, which is the inface of the revived cuesta. The upper part of this cuesta rises as a ridge 200 feet high above the surface of the lake, but the greater part is submerged. The escarpment can be traced to and around the western end of Lake Ontario (where it is breached by the valley

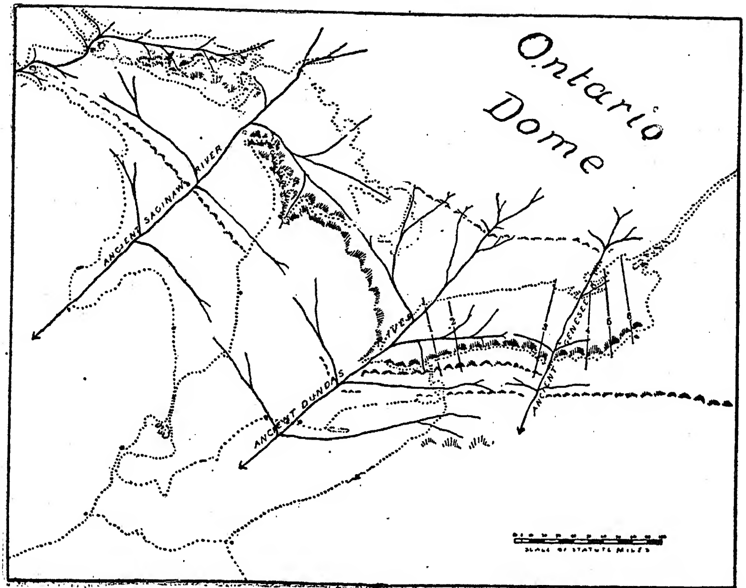


FIG. 617. — Map of the ancient drainage system of the southern and western part of the Ontario dome; early stage. The present hydrography is dotted; the principal cuesta-fronts are indicated.

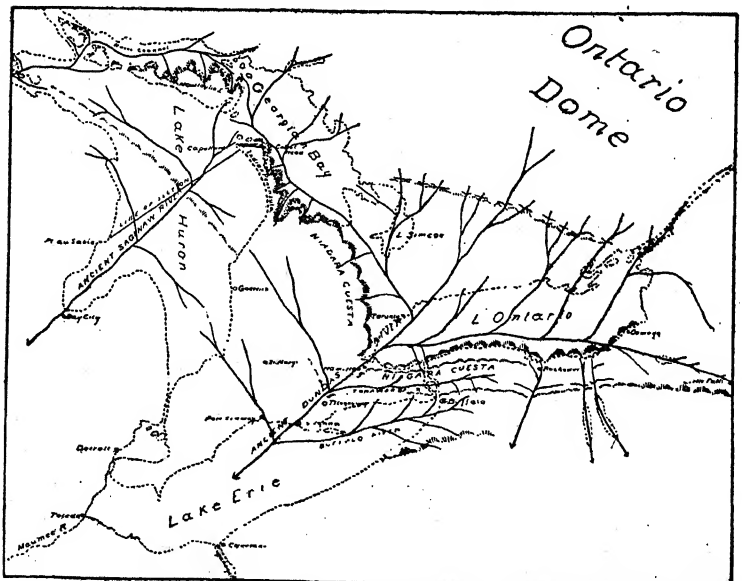


FIG. 618. — Map of the ancient drainage system of the southern and western part of the Ontario dome, showing a later stage when by capture the headwaters of the other consequents have become tributary to the Dundas River.

of the drift-buried consequent above mentioned — the Dundas River) and throughout the peninsula which divides Georgian Bay from Lake Huron, continuing beyond the gap, in Manitoulin Island. A second escarpment, formed by a higher limestone bed (the Onondaga), can be traced east and west through the city of Buffalo, across western Ontario in a northwest direction, where it is chiefly buried by glacial drift, and diagonally across Lake Huron from near Goderich, Ontario, to Mackinac Island. Even where submerged, it is clearly shown by soundings in Lake Huron to have a height of about 400 feet (Fig. 619). A third escarpment forms the front of the Alleghany Plateau in southwestern New York, and extends along the western margin of Lake Huron. The lowland in front of it is partly occupied by the eastern end of Lake Erie. The general relationship of the radial streams and revived cuestas is shown in the diagram on page 760 (Fig. 653).

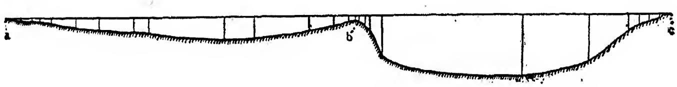


FIG. 619. — Cross-section of Lake Huron from Point au Sable, (*a*) Michigan, across nine fathom ledge (*b*) to Cape Hurd, (*c*) Canada, showing the submerged Onondaga cuesta and the lowland in front of it.

These three escarpments can be traced eastward through New York state, gradually approaching one another as the Mohawk River is reached, because the softer beds, which form the lowlands on the west, die out eastward. They finally unite to form the ridge known as the Helderberg Mountains in eastern New York, culminating in the Catskill Mountains, which project as a group of monadnocks above the surface of the peneplane.

These various cuestas and lowlands have the relation to the center of the Ontario Dome that normal cuestas and lowlands have to their oldland, and they are sometimes referred to as normal cuestas in the second cycle of erosion. They are, however, the remnants of the rimming strata of a peneplaned dome, which, because of further elevation of that dome, have undergone renewed dissection with the revival of an incomplete rimming cuesta topography.

Nashville Dome. — As a final example of a dissected dome of gently dipping strata, the Nashville Dome of central Tennessee

may be noted. Although a structural dome, it now forms a topographic basin, the Central Basin of Tennessee. This is due to the fact that after the peneplanation of this dome, the central area exposed only soft strata, and these were largely cut away down to a lower series of hard strata by the tributaries of the radial streams which dissected the dome on renewal of uplift. The chief of these streams is the Tennessee River, which has cut a narrow, gorge-like valley in the surrounding rim. The rim is continuous except for the breaches by the radial streams, which lie chiefly upon the western side. It is formed by the edges of the harder strata which overlie the softer ones not far from their position of outcrop after the peneplanation. The central depression (the topographic basin) is about 70 miles across, and

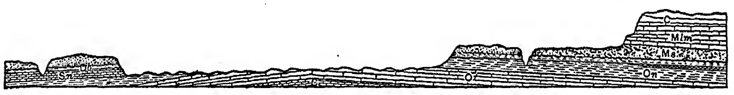


FIG. 620. — Section of the Nashville dome, showing the center eroded into a topographic basin or encircled lowland, the so-called Central Basin of Tennessee. *C*, Cambrian; *Ot*, Ordovician (Trenton) limestone; *On*, Ordovician (Nashville) shale; *Sn*, Silurian (Niagaran) limestone; *Db*, Devono-Mississippian shale; *Ms*, Mississippian sandstone; *Mlm*, Mississippian (Mountain) limestone; *C*, coal measures; Length of section about 120 miles. (After Safford.)

its bottom, which is about 600 feet above sea-level, is formed by the lower series of hard rocks and has a gently undulating surface (Fig. 620). Outliers from the surrounding plateau characterize it in many places as we approach the rimming margin. The Cincinnati Dome is a larger but less perfect example of similar character.

Shallow Basins

Shallow structural basins are the complements of the flat domes with which they are commonly associated. In America the best example is found in the lower peninsula of Michigan (Michigan Basin), while in Europe the Paris Basin is the best known example. Both of these represent basins not in the first cycle of erosion, for both have suffered peneplanation and the present topography is a revival in the second or later cycle. As a result of this, the strata now form a succession resembling a nest of plates, the largest at the bottom and the smallest at the top, the successive edges of the plates forming the outer rims of the several formations.

By the excavation, during the second cycle, of subsequent valleys upon the outcrops of the softer beds there are produced con-

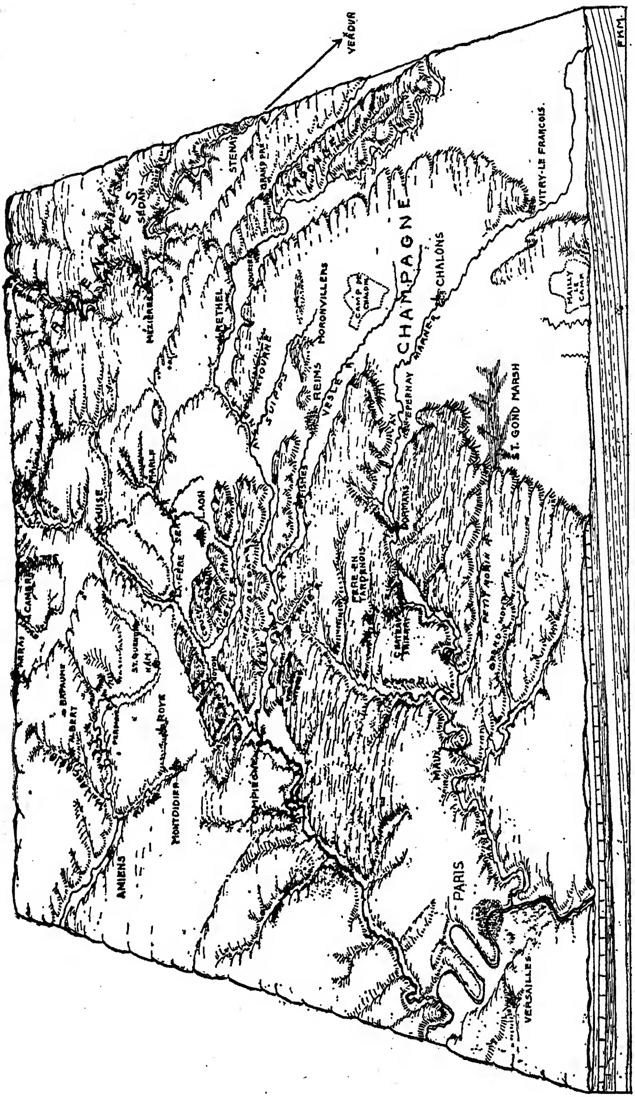


FIG. 621. — Block diagram of the eastern and northern part of the Paris Basin, showing the rimming outward facing cuestas and annular lowlands. (Drawn by F. K. Morris.)

centric annular lowlands. The outcropping edges of the hard strata form cuesta ridges, the escarpments of which face outward in all directions. This is especially well seen in the eastern

part of the Paris Basin, where a succession of such outward-facing escarpments, separated by broad flat valleys, marks the approach from Germany towards Paris, which lies in the center of the basin. These escarpments form, indeed, a series of huge steps up which, or through the gaps in which, invading armies from the east must fight their way; while the gentle slope from the top of each step toward the foot of the next inner one, and finally toward Paris, makes the approach from the west an easy one (Fig. 621). The heights of Nancy and Metz form the easternmost of these escarpments (Middle Jurassic). Beyond them, nearer Paris, lies the Woevre lowland, west of which rises the second escarpment (Upper Jurassic), which has to be ascended to reach Verdun. Still farther west lies the Wet Champagne lowland separated by the chalk escarpment from the Dry Champagne lowland,

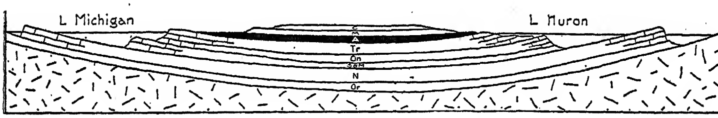


FIG. 622. — Cross-section of the Michigan Basin showing the rimming cuestas which are largely submerged. *Or*, Ordovician; *N*, Niagaran; *S* & *M*, Salinan and Monroan; *On*, Onondaga; *Tr*, Traverse; *A*, Antrim black shale; *M*, Mississippian; *C*, Coal Measures.

which in turn is bounded on the west by the Rheims-Epernay-Sezanne escarpment (Tertiary), the last to be ascended before reaching the center of the basin and Paris. These escarpments are also, though less perfectly, developed on the south and west, but on the northwest they are obliterated by the English Channel. Between the Ardennes Mountains and Calais on the coast they are not developed because, owing to a tilt in the basin, erosion has not gone deep enough. Hence the approach to Paris through Belgium is the only one which avoids these great step-like natural defenses.

The center of the Michigan Basin, in which Alma lies, is surrounded by a similar series of outward-facing escarpments, but owing to the heavy glaciation of the region the lowland valleys are generally filled with drift and obliterated, while others are occupied by the waters of Lakes Huron and Michigan. If these lakes were drained, central Michigan would be well defended by cliffs from Canadian and Wisconsin approaches, though easily accessible from the south (Fig. 622). (See also Fig. 516, p. 600.)

The Erosion Cycle on Anticlines and Synclines

The First Cycle. — The erosion of anticlines proceeds much after the manner of that on steep domes, except that the initial consequent drainage is not radial, but consists of a series of parallel streams on either side of the anticline and flowing away from its axis. These lateral consequents carry the drainage into the synclines, where the initial longitudinal consequent streams, *i.e.*, those flowing along the axis of the fold, are situated (Fig. 623). Only at the ends of the anticlines, where these flatten out or pitch, is the radial form of initial drainage partly realized.

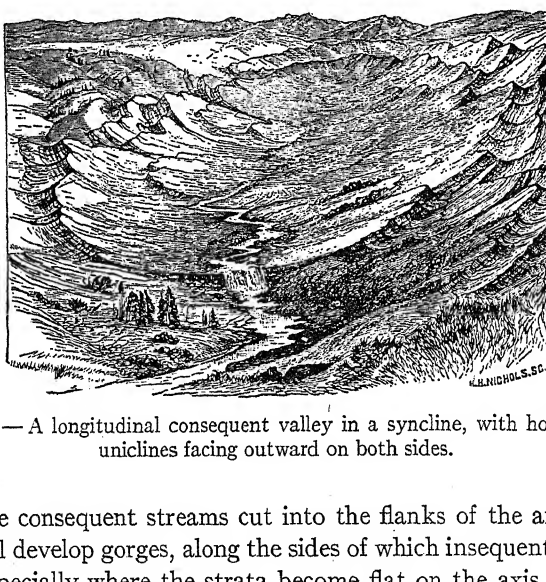


Fig. 623. — A longitudinal consequent valley in a syncline, with hog-backs or uniclines facing outward on both sides.

As the consequent streams cut into the flanks of the anticlines, they will develop gorges, along the sides of which insequent streams arise, especially where the strata become flat on the axis. In the course of time there will be opened a longitudinal breach in the axial portion of the anticline (Fig. 624, I). If a hard stratum forms the capping rock, with a softer one beneath it, this breach will be enclosed by cliffs broken only by the narrow gaps through which the consequents flow. Continued erosion will not only lengthen this breach on the axis (Fig. 624, II), but will push the sides farther and farther apart, that is, down the flanks of the anticline. If a second hard stratum is discovered on the axis of the anticline, this will form a central ridge, flanked on either side by longitudinal subsequent valleys.

Further erosion may open up a new longitudinal valley in the top of this axis, at the same time pushing the sides of the older

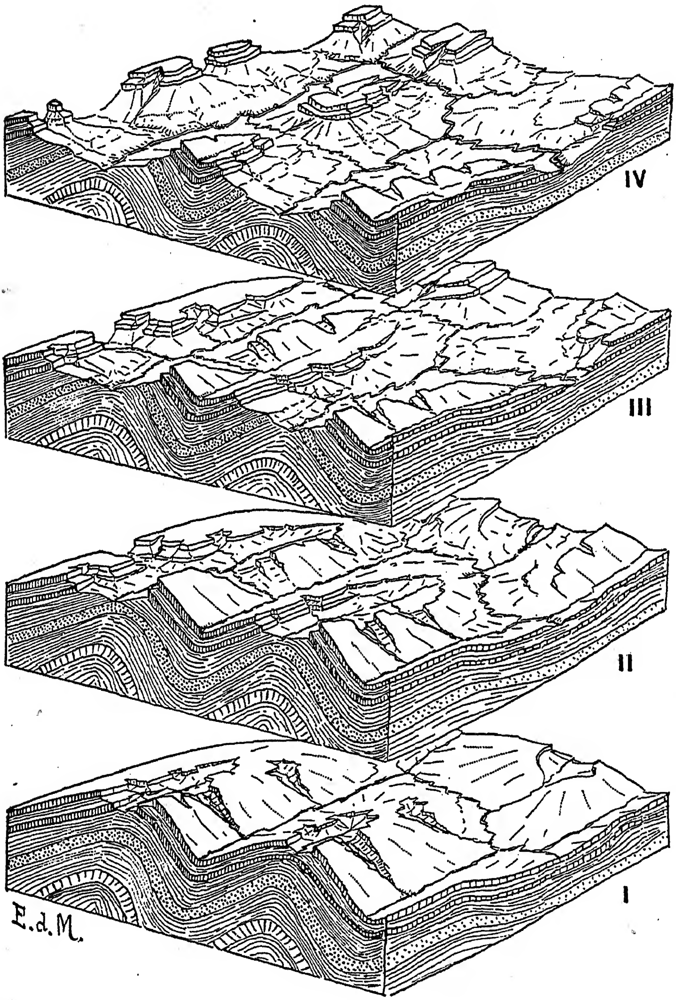


FIG. 624. — Diagrams showing the development of river systems in anticlinal folds with anticlinal valleys as the end product (IV). As a result of this erosion the streams flowing in the synclinal valleys are diverted by capture and the main streams become anticlinal. (After de Martonne.)

valleys farther down the flanks. Thus a series of *uniclinal* ridges is produced, facing the center of the original anticline. The drainage system produced will at first comprise longitudinal subse-

quent streams which occupy the valleys on the softer strata parallel to the ridges, and transverse consequents passing through gaps in the ridges to the longitudinal consequent streams which flow down the axis of the syncline. Some of the larger transverse consequent streams may cut so deep that their tributary subsequents will encroach upon the territory of adjoining weaker consequents, which they may finally behead, carrying the captured drainage to the master stream. If this happens, the original water-gap through the ridge formed by the weaker consequents, will be abandoned below the elbow of capture and become a dry notch in the ridge. It is then known as a wind-gap.

In the following diagram (Fig. 625) a stream (*Q*) flowing towards

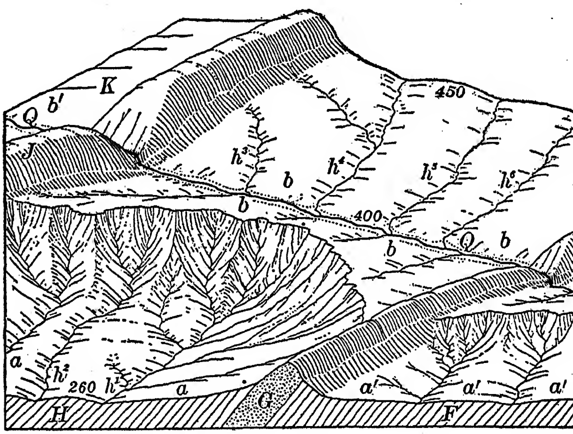


FIG. 625.—Diagram illustrating the imminence of river capture. (After Davis.)

the anticlinal valley on the right across two hard strata *G*, *J*, is encroached upon by another flowing upon soft strata *H*, the valley of which, as shown by the figures, is much lower. In the next stage, shown in diagram Fig. 626, the capture of the upper part of the stream (*Q*) has been completed.

When the breaching of the anticline has proceeded as far as the altitude of the land with reference to the base-level of erosion permits, a series of parallel uniclines or hog-back ridges and longitudinal strike-valleys, with generally a central axial or anticlinal valley, has been produced, the cut edges of the ridges successively facing the center of the anticline. Further erosion will result in the lowering of these ridges, and when they have

nearly disappeared, a peneplane will be formed, the surface of which will be marked by a series of parallel belts of alternating hard and soft strata; but none of these produce marked relief features. Where the ends of the anticline pitch beneath the erosion surface, the corresponding strata will curve around from opposite sides, joining along the axial line, or better, a continuous curve will unite the corresponding strata on opposite sides, forming canoe-shaped valleys (see Figs. 508, p. 595, and 514, p. 598). As the hard strata which confined the longitudinal subsequents to their respective valleys are reduced to the level of the peneplane, these streams may shift their location, meandering aimlessly across hard

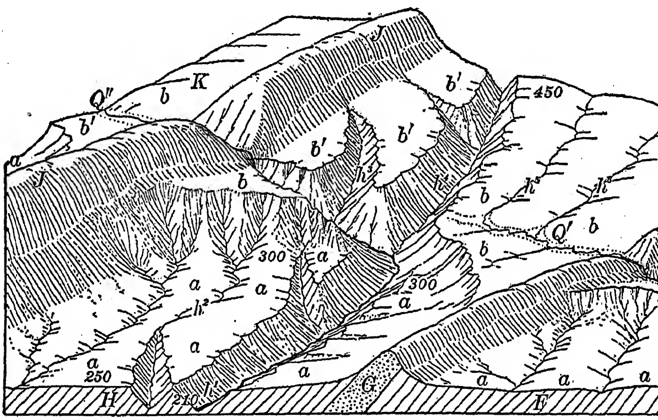


FIG. 626. — Diagram showing the same region with the capture completed. (After Davis.)

and soft strata alike. Thus the initial character of the drainage is destroyed.

The Second Cycle. — If a peneplaned region of anticlinal and synclinal structure is elevated, rejuvenation of the streams will take place, and these will begin to cut downwards where they were located at the time of the uplift (Fig. 627). If, as generally happens, the surface of the peneplane becomes warped or slightly tilted on uplift, the direction of the new drainage will be determined by the slope thus produced, and the streams may begin to cut downward across hard and soft strata alike. So soon as a master stream has begun to incise its bed beneath the surface of the peneplane, lateral streams will begin to open out valleys along the softer strata, leaving the harder in relief, and thus the

original topography of longitudinal valleys and parallel uniclinal ridges will be revived (Fig. 628). By capture of the weaker streams which flow across the strata, wind gaps are produced, and the drainage all becomes tributary to the master stream or streams of the region.

Recognition of the Second Cycle. — How can we recognize that a dissected anticlinal region is in the second cycle, when the ridges all stand out in bold relief and the valleys are occupied by longitudinal streams, tributary to a transverse consequent which

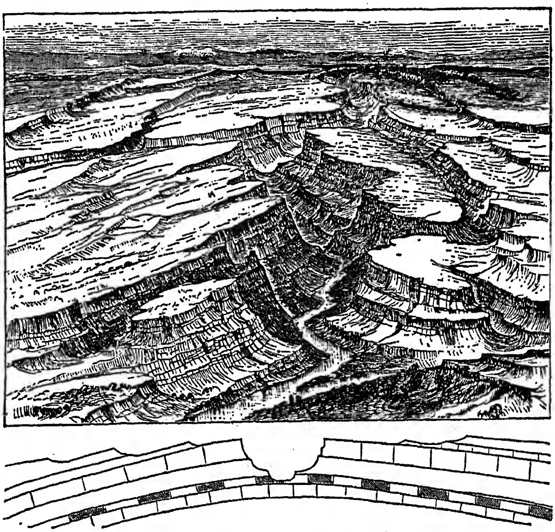


FIG. 627. — A stream incised upon the axis of a broad anticline, where it happened to be located at the beginning of a new cycle of erosion.

has cut gaps for its passage across the successive ridges? If we were dealing with a single anticline, it would probably be difficult to determine the cycle, though here, too, certain guiding principles might help to solve the problem. In the first cycle, the drainage from the corresponding longitudinal valleys on opposite sides of the axis is carried outward in opposite directions. It is, however, conceivable that by capture the entire drainage system of one side might be reversed and carried out in the opposite direction. While this might happen in the case of one anticline, it is extremely doubtful that by capture the entire drainage can become tributary to a stream which, as the result of such capture, crosses two anticlines and all the uniclinal ridges derived from them. Still more

doubtful does it become when the number of parallel anticlines is more than two. If a master stream has cut gap after gap across all the uniclinal ridges of several parallel anticlines, carrying the drainage of all the longitudinal valleys and of the original syncline as well, it is practically certain that this stream was not built up from progressively captured portions of other streams, but that it represents a new stream formed upon the surface of a sloping peneplane. This stream cuts its channel regardless of hard and soft strata; for there is no chance for readjustment during the cutting of the channel, because such a stream controls the drain-

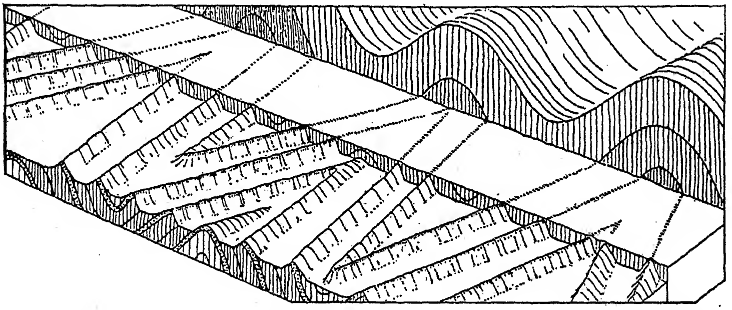


FIG. 628. — Diagram showing the development of a peneplane from anticlinal ridges and the reappearance of the uniclinal topography after elevation and renewed erosion. This is the type of structure found in the Appalachians. (After Davis.)

age of the region, and no valley can be cut by any of its tributaries which is lower than the floor of the valley of the master stream.

It should, however, be noted that many if not most of the phenomena here cited may be explained by the hypothesis of an *antecedent stream* in the first cycle; but there are other criteria which will serve to determine the applicability of that hypothesis. Antecedent streams are discussed in a later section.

It is because of the existence of a number of such transverse streams, which cut across all the ridges of the region, and moreover, have a meandering course, that the Appalachian Mountains are believed to be in at least a second cycle of erosion (Fig. 629). The Susquehanna is the most prominent of these transverse streams, and its tributaries have opened up again a large part of the valley system of the present Appalachians of Pennsylvania, etc. This opening of the Appalachian valleys was essentially coincident with the opening of the cuesta-like topography of the Ontario and other

domes to the north, and the drainage accomplishing the latter was in part carried out by the Susquehanna.

As a result of this erosion in the second cycle, the axes of the original synclines, now high above the new base-level of erosion, have often been left in relief by the cutting of the valleys on either side to a greater depth. Thus synclinal mountains are actually produced, these being a characteristic feature of some parts of the Appalachian system.

When the center of the anticline consists of hard rocks, erosion progressing in the manner outlined will leave a central ridge in-

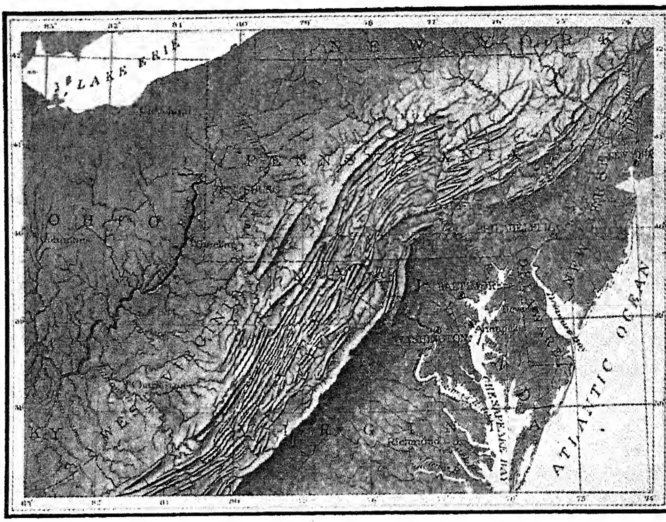


FIG. 629. — Map of Northern Appalachians. (U. S. G. S.)

stead of a valley. This central ridge seen in parts of the Appalachians will be bordered on either side by uniclinal ridges formed by the hard strata of the sedimentary series (Fig. 628). Such uniclinal ridges or hog-backs, as they are called (Fig. 630, I, II), which have been developed in the first cycle of erosion, may become obliterated again when the region approaches a condition of peneplanation. Renewed elevation will steepen the inclination of the layers (Fig. 630, III), after which erosion will once more model out the hog-back, or uniclinal topography (Fig. 630, IV).

This has been essentially the later history of the Rocky Mountain Front Range, though by the further development of thrust faults this history has been rendered more complex. The central

axis of the range consists of crystalline rocks (granites, etc.), and is margined on either side by pronounced hog-backs, formed by the harder strata of the Mesozoic series which once extended across the crystallines. Typical examples of such hog-backs are shown in Figs. 631, 632. The upturned strata along the mountain front, will, if they are sandstones or other porous rocks, take in surface waters and so form a head for artesian conditions farther out in the plains, as shown in the section of the Dakota artesian system on p. 424 (Fig. 353). As the strata are flexed only near the mountains, and change toward horizontality away from these, it is evident that as the hog-back is pushed

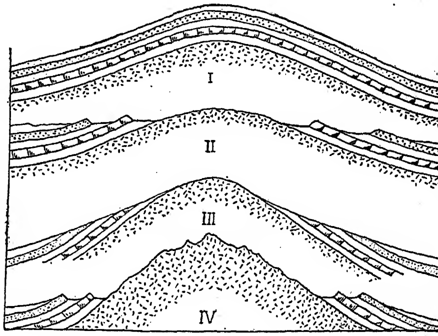


FIG. 630. — Diagrammatic sections representing the development of hog-backs. I, a simple anticlinal ridge consisting of hard and soft sediments overlying crystalline rocks; II, the same after erosion and development of hog-backs (uniclines) on opposite sides; III, the same region after peneplanation and further arching; IV, Development of the hog-backs in the second cycle of erosion.

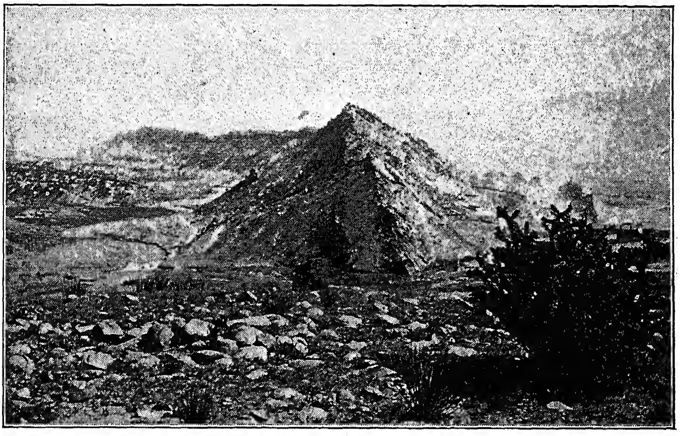


FIG. 631. — Hog-back of Dakota sandstone, near Canyon City, Colorado. The ridge-making hard stratum dips steeply to the right. A second, minor ridge is formed by another hard sandstone on the right. Valley of the Graneros River. (C. D. Walcott, photo, U. S. G. S.)

farther away from the mountain by erosion, the steepness of the dip of its strata will decrease, until it becomes so low that the

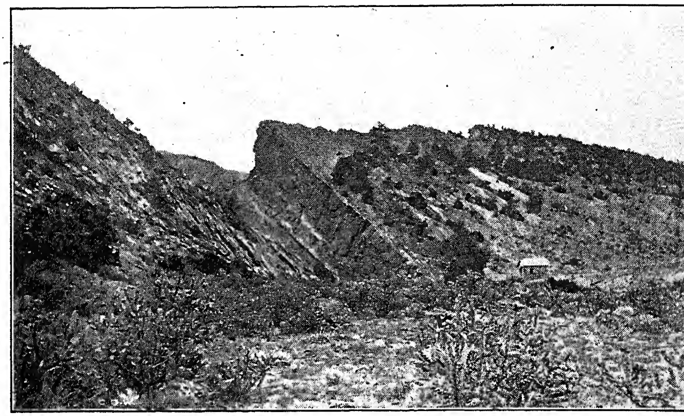


FIG. 632. — Hog-back near Colorado City, Colorado. (I. C. Russell, photo.)

beds have the appearance of gently dipping coastal plain strata, and the hog-back changes to a cuesta. Still farther away, where the strata are absolutely horizontal, a step topography is produced

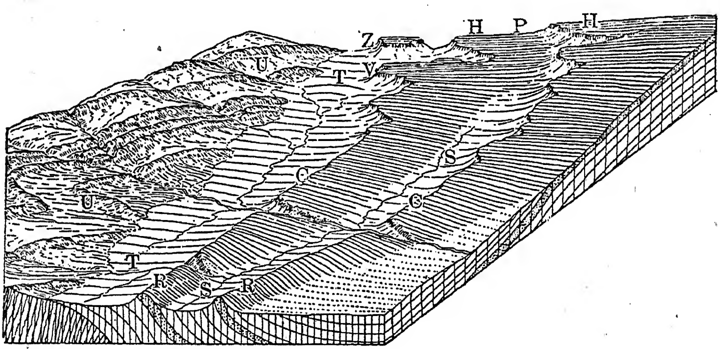


FIG. 633. — Hog-backs *RR*, changing into cuestas (*CC*) and these into steps (*HH*) by progressive flattening of strata; *UU*, oldland; *TT*, inner lowland; *SS*, second lowland; *P*, plateau between steps; *V*, nose; *Z*, outlier. (After Davis.)

by the edges of the hard formations. In some cases all of these stages may be observed along a line of outcrop, as shown in the preceding diagram (Fig. 633) where the hog-backs (*RR*) pass into

cuestas (*CC*) and these into steps (*HH*). Such a change is also seen along the present eastern front of the Appalachians, where the Helderberg front, of the cuesta type, passes southward into the uniclinal ridge through which the Delaware River has cut its water-gap (Fig. 634).

Complexly Folded Strata. — When erosion attacks complexly folded strata, the process, though following the general laws observed in the case of simple folds, is correspondingly more complicated, and the erosion forms produced are more diverse. In-

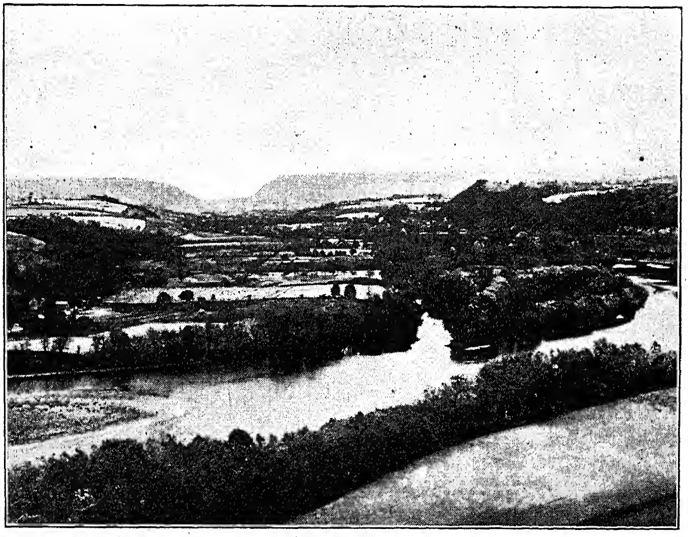


Fig. 634. — View of Delaware Water-Gap from the Great Valley, showing the even sky line of the mountains and the abrupt cut of the water gap. (U. S. G. S.)

stead of long, regular ridges, such as those of the Appalachians, individual peaks and irregular ridges, such as those of the White Mountains, the Alps, the Caucasus, and others, result. In these, moreover, glacial erosion has aided in the sculpturing process, as will be set forth later. Peneplanation of such a region is apt to leave peaks of harder rock standing above the peneplane level as monadnocks. Such is Mt. Monadnock in southern New Hampshire, the type of residual erosion peaks, which from some points of view has almost the regularity of outline of a volcanic cone (Fig. 635).

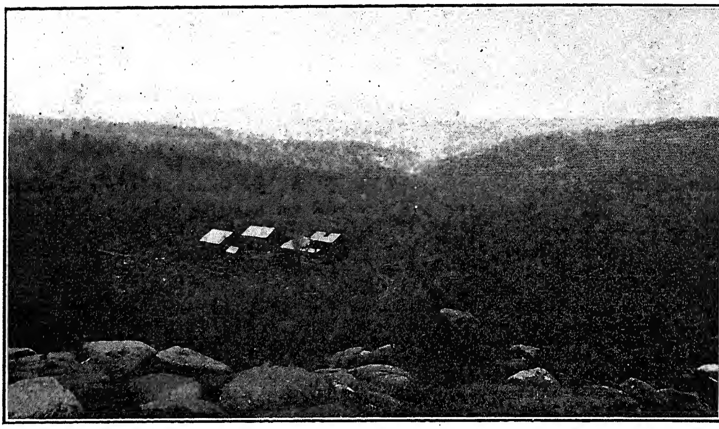


Fig. 635. — The New England peneplane with Mt. Monadnock (New Hampshire) rising above it. From Beech Hill, Keene, N. H. Tertiary valleys in the foreground. (Gardner Collection of Photographs, 2634. Courtesy Geological Department, Harvard University.)

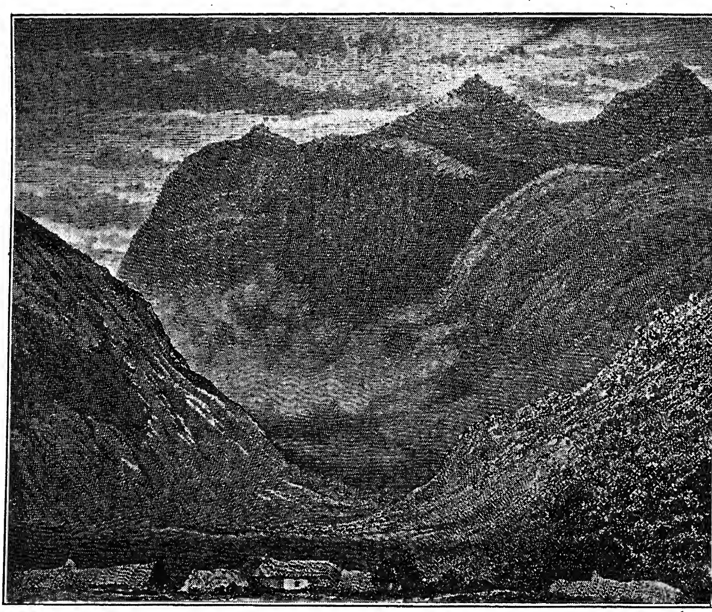


Fig. 636. — Glen Coe, a glaciated stream valley in the Scottish upland. The glens of Scotland are splendid glacial troughs, of which Glen Coe is a typical example. (Courtesy of D. W. Johnson.)

The New England peneplane was uplifted with a tilt, so that there is a rise of the surface inland. Large portions of the peneplane are still intact, forming broad uplands beneath which the streams have intrenched their courses. The Scottish Highlands region, on the other hand, represents a much more thoroughly dissected peneplane, so that the upland has been reduced to narrow ridges between the glens, which are the product of a later cycle of erosion by streams and glaciers (Fig. 636).

Antecedent Streams. — Streams cutting across anticlinal or complex mountain systems are not necessarily inherited from a former cycle or developed upon a peneplane surface. They may represent streams across the path of which a series of folds or fault blocks have arisen at such a slow rate that the downward cutting of the stream kept pace with the rising of the folds or other structures which would otherwise have diverted the stream. Such streams are called *antecedent*, because they existed in the region before the structure in question made its appearance. The Columbia River is believed to have such an antecedent relation to the Cascade Mountains which rise across its course and are cut by it. The Meuse River of France is also believed to be antecedent with reference to the Ardennes highland, through which it cuts a deep, narrow gorge or cañon. Although the uprising of this highland of ancient strata across the river path was so slow that the Meuse was able to keep pace with it by cutting downward, and so maintain its course, it lost its tributaries which were diverted by capture to other streams not so handicapped (Figs. 637, 638).

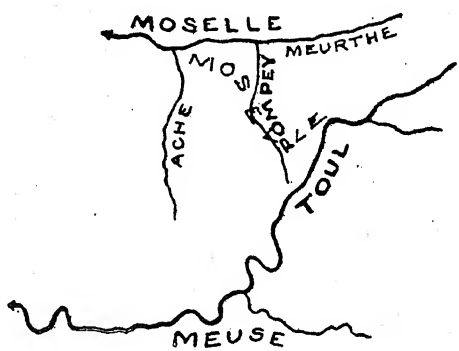


FIG. 637. — Map of the ancient Meuse when the Toul, now diverted, formed a part of it. The Moselle of that time included the Meurthe (a tributary to the modern Moselle) and the Pompey, a tributary of that time, but now with the Toul forming a part of the modern Moselle (see Fig. 638). (After Davis.)

Superimposed Streams. — There is still another way in which streams can be forced to cut across rock structures, hard and weak alike, without being able to adjust themselves, by selective erosion, to the weaker structures. This is effected where a country of diverse structure is covered by a deposit of coastal plain strata which present a new surface upon which rivers may develop irrespective of the character of the underlying rock. Having acquired a certain course, determined by the slope of the coastal plain strata, the river will be forced to continue downward cutting into the underlying rocks, no matter how diverse their structure. Eventually the coastal plain strata may be largely or wholly removed by erosion, revealing the underlying rock and the topographic features which marked its surface before the coastal plain strata were deposited upon it, and these may be entirely out of harmony with the course of the river superimposed upon them. The lower course of the Connecticut through the crystalline rocks of the New England upland is believed to be due to superimposition of the course acquired upon a former covering of coastal plain strata, now wholly removed from that region by erosion.

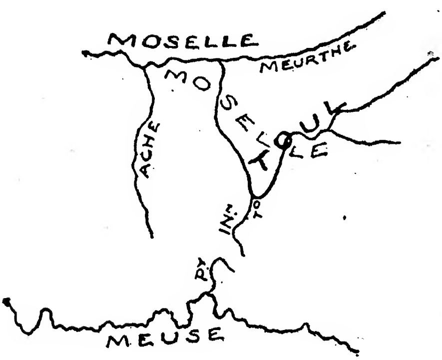


Fig. 638. — Map of the Meuse and Moselle, showing the formation of the modern Moselle by capture of former tributaries to the Meuse. (After Davis.)

Special cases of superimposed streams are occasionally met with. One of the most interesting is that of the famous Lake District of Northwestern England. This is a roughly oval area, formed of complexly folded older Palæozoic shales, sandstones, and igneous rocks, with many high mountain peaks formed by resistant strata, between which the river valleys expand in a series of beautiful long and narrow lakes which have made the region famous. The area is almost completely surrounded by belts of late Palæozoic and younger strata, including the Carboniferous limestone of the English geologists (Mississippian age), the Coal Measures which

overlie these, the next higher Permian sandstones, and finally, on the west, the New Red sandstone beds (Triassic). Wherever

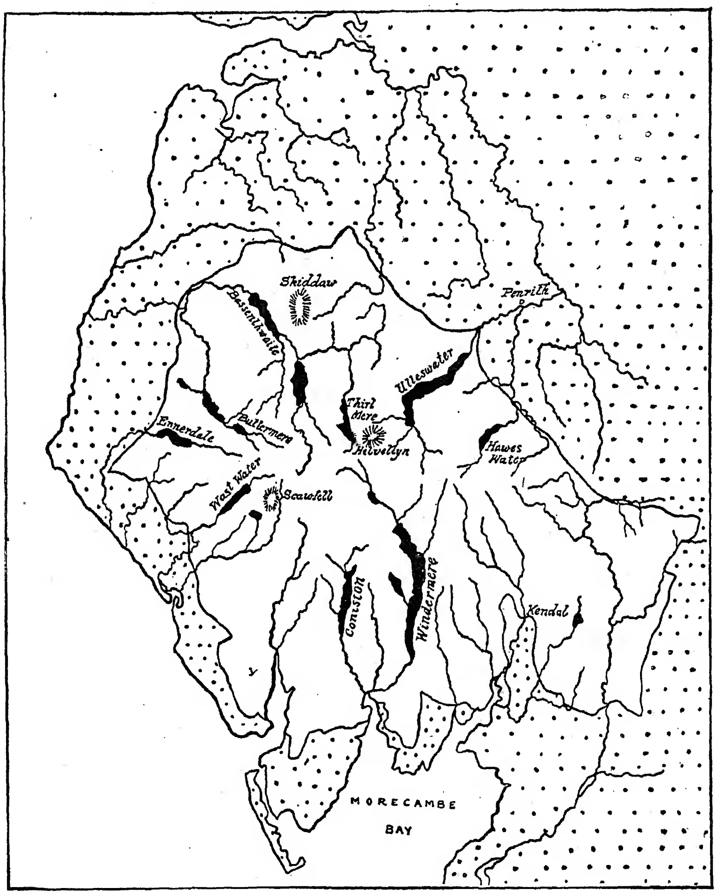


FIG. 639. — Map of the Lake District, showing radial drainage. The dotted area represents Carboniferous and younger rocks, gently dipping away from the center of the dome. The plain area is formed by Silurian and Ordovician strata much deformed and with a general N. E. and S. W. strike. (From Lake and Rastall. Textbook of Geology.)

these rocks rest upon the older Palæozoics, they are found to have an unconformable relationship, these younger rocks being but slightly disturbed, while the older ones are strongly so. Moreover, with negligible exceptions, these younger rocks dip away in

all directions from the center of the area which they surround, and this indicates that the region was a dome once covered by these younger strata which have since been eroded from the central area. The radial drainage developed upon this dome has become superimposed upon the underlying rocks of complex structure as they were uncovered, and hence, despite this complex structure and the general northeast and southwest strike of the folds of the older strata, the drainage is a radial one, wholly out of harmony with the rock structure of the region, except locally where adjustment has taken place. There can be no doubt that the general direction of these streams is inherited from their courses on the domed strata which formerly covered this region, and along the margins of the area, where they still lie within these younger strata, they have the normal arrangement of radial consequents (Marr). The lakes in these river valleys owe their origin in part to glacial erosion and obstruction by drift.

The map on the preceding page (Fig. 639), copied from Lake and Rastall, shows the radial arrangement of the lakes of this district and the streams which determined their position.

CHAPTER XXIII

THE SCULPTURING OF THE EARTH'S SURFACE (Continued)

THE EROSION CYCLE IN A FAULTED REGION

A REGION that has been subjected to extensive faulting, presents some interesting conditions which exercise a controlling influence upon the topography produced by erosion. We can consider only the simpler types of features produced by faulting, but they will serve to point the general principles of which cognizance must be taken in the interpretation of the land forms produced in a faulted region by the agencies of erosion.

The Fault Block or Block Mountain

Characteristics of Block Mountains. — In certain regions the crust of the earth appears to have been broken into a series of parallel blocks, and by what appears to be a tilting movement of these blocks one side has been raised and the other depressed, resulting in the formation of parallel ridges and valleys of triangular cross-section, each characterized by a long, gentle slope on one side and a short abrupt slope on the other. This type of *block faulting*, as it is called, may be illustrated by placing upon the table a row of books or blocks of the same size and thickness, and then tilting the whole series in one direction, when the upper edges of the books or blocks will produce a series of ridges and valleys of the type described (Fig. 640 *a*, *b*), although it must be clearly borne in mind that such regularity does not exist in nature. When these tilted fault blocks are large enough, they constitute block mountains. In a region of horizontal strata such block faulting will produce a succession of hog-back-like ridges (Fig. 640 *c d.*) but these differ from the hog-backs of erosion, the true uniclines produced upon the side of an anticline, in the fact that each of the tilted fault blocks shows the same succession of strata, whereas

in a series of hog-backs of erosion, the stratum capping each successive ridge will be a different one, either higher or lower, according to the order in which the successive hog-backs are examined. The capping bed of the inner hog-back (*i.e.*, that nearest the center

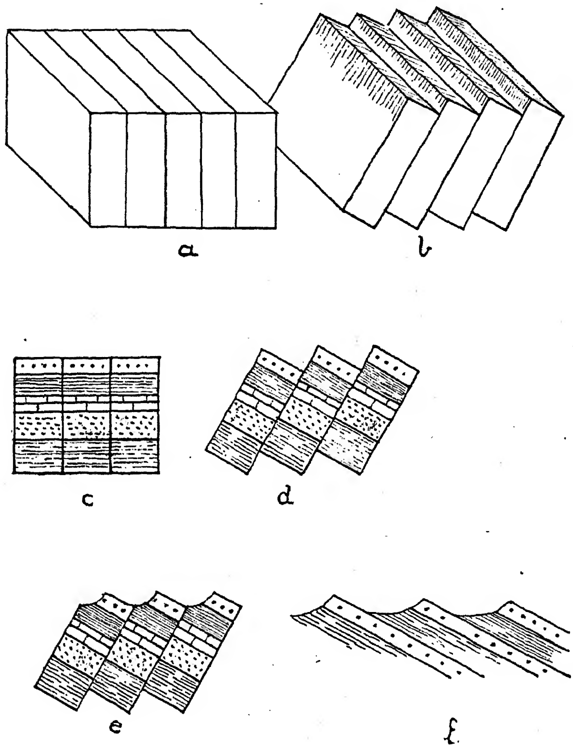


FIG. 640. — Diagrams illustrating block faulting. *a*, *b*, ridges produced by tilting of blocks; *c*, region of horizontal strata intersected by vertical fissures; *d*, the same after tilting, — note the repetition of the strata in the successive blocks; *e*, the same series with the fault faces of the blocks eroded; *f*, a series of normal uniclines showing a similar appearance, but each ridge is capped by a different bed.

of the original anticline) will pass under that capping the next outer one and the capping bed of this one again under that of the one next outward from it. This is shown in diagram *f* in the illustration (Fig. 640) which should be compared with the diagram *e* of the same figure. A more complex and irregular type of block faulting has already been illustrated in Fig. 557 *a*, p. 633. An actual

example of complex block faulting on a small scale, from Nevada, is illustrated in the following map and section (Figs. 641, 642).

Typical Examples. — Typical examples of mountains formed by the tilting of large blocks which themselves are broken into minor blocks, are found in the Sandia and Magdalena mountains

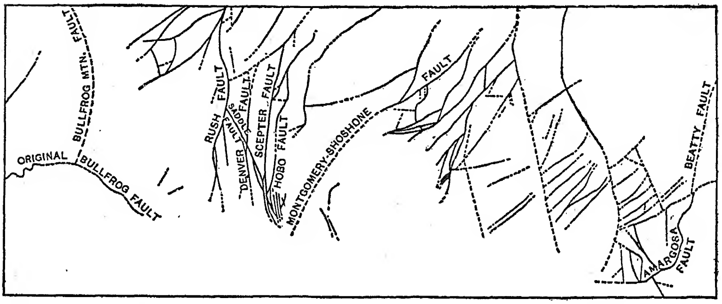


FIG. 641. — Plan of the principal faults in the Bullfrog district, Nevada. (Emmons, U. S. G. S.)

of New Mexico. The displacement occurs in originally horizontal strata underlain by crystalline rocks (Fig. 643, Johnson). Block faulting in regions of more complex structure is seen in the Basin Ranges of Utah and Nevada. On the eastern edge of the Great Basin stands the block which forms the Wasatch Mountains.

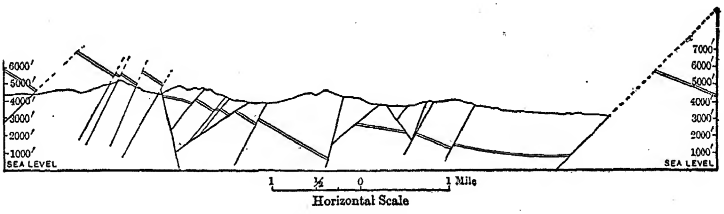


FIG. 642. — Diagrammatic section illustrating fault block displacements in the Bullfrog district, Nevada. (Emmons, U. S. G. S.)

Its surface is tilted so as to slope eastward and its fault surface faces westward. On the opposite side of the Great Basin stands the block which forms the Sierra Nevada Range. Its fault face is on the east, and its long back slope drops off gently to the Valley of California on the west. Between the two are many narrow ridges from 10 to 50 miles in length which represent modified fault blocks of this type. The fault faces of some are turned east, of others west.

Complex block faulting has also occurred in a number of cases. The general relationship is shown in the lower diagram on this page, after Le Conte (Fig. 644), the faulting being interpreted as the breaking down of a great arch.

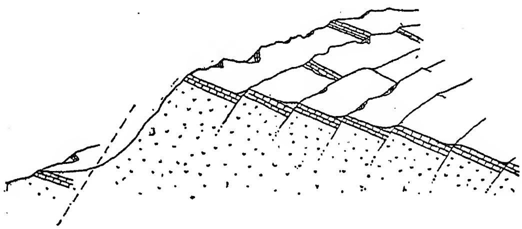


FIG. 643. — Block faulting, Sandia Mountains. The mass consists of crystalline rocks, shown by dots, covered by limestones and other sediments, which originally were horizontal. A single great fault forms the left-hand face of the mountain, which consists of a tilted block, broken into minor blocks by lesser faults. (After D. W. Johnson.)

The block mountains of the Great Basin ranges are not generally formed from horizontal strata, but are complex. The Wasatch block contains many crystalline and metamorphic rocks; the Sierra Nevada block is in large part igneous. In the ranges within the Basin, the strata are part of an old folded mountain system similar to that of the Appalachians and, like that, peneplaned. Instead of simple elevation at the beginning of the second cycle, the Great Basin region then suffered block faulting. The direction of the faults does not conform to that of the old folds, *i.e.*, to the strike of the strata, but is often obliquely across them. This relationship is shown in the following diagram (Fig. 645). In some of the Basin Ranges slight faulting or uplift of the fault block has occurred in comparatively recent times, and some are probably still undergoing movement (Fig. 646).

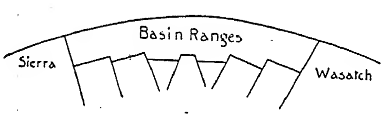


FIG. 644. — Generalized cross-section of the Great Basin from the Sierra Nevada to the Wasatch, showing the origin of the block mountains of the Basin Ranges by collapse of a former arched surface. (After Le Conte.)

Erosion of Block Mountains. — The streams which come into existence upon a faulted block mountain are of two types, one flowing down the back slope of the tilted block, that is, the original

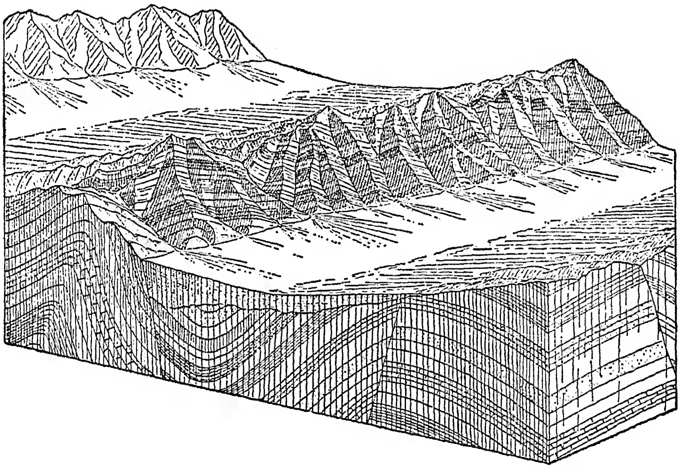


FIG. 645. — Diagram illustrating the development of the block mountain topography of the Basin Ranges. The region is one of folded Palæozoic strata, their folds forming the ancient Palæocordilleran mountains. Peneplanation ensued, followed by block-faulting, after which erosion carved the present mountain topography, while the depressions between the blocks were partly filled by the waste from the mountains. (After Davis.)

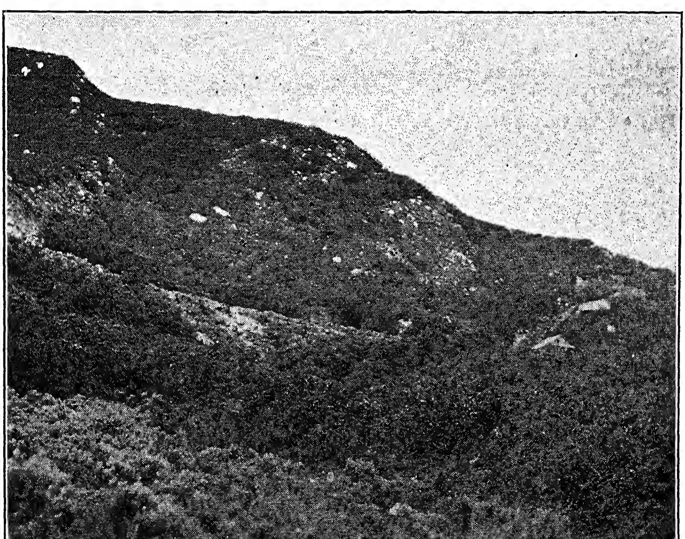


FIG. 646. — Recent fault crossing moraine. Wasatch Mountains, Utah. (F. J. Pack, photo.)

surface of that part of the land, whether it was of horizontal strata or a peneplaned surface; the other flowing down the much steeper fault scarp. The first type may be compared to the consequent streams of an anticline, or if the tilting is slight, to the normal consequent of the coastal plain. The second type, that flowing down the fault scarp, may be compared to the obsequent stream of the cuesta, or the similar obsequent stream on the inner side of the hog-back. In a measure, of course, both stream types developed on the fault block are consequent, one being the dip-slope consequent, the other the fault-scarp consequent, and they are so classed by many physiographers.

Because of the greater steepness of the fault scarp of the tilted block, the streams upon it will have greater erosive power than

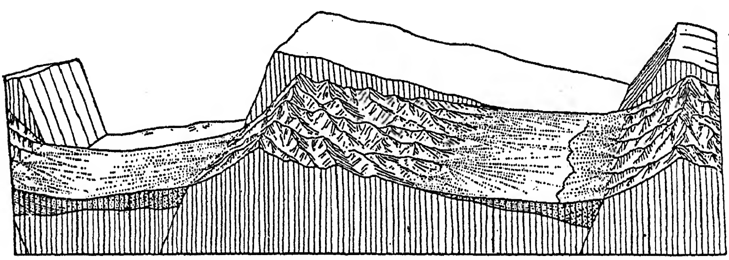


FIG. 647. — Diagram showing mountains and valleys due to block faulting in the background, and the dissection of the blocks and filling of the valleys, in the foreground. A stage of maturity has been reached in the development of these mountains. (After Davis. *Erklärende Beschreibung der Landformen.*)

those on the back slope. In consequence, the divide between the two types of streams flowing in opposite directions, which in the beginning was at the crest of the tilted block, is pushed away from the edge of the fault scarp, and the drainage basin of the fault-scarp stream will encroach more and more upon that of the outer-slope stream. This is true of course, primarily, where the two stream systems receive an approximately equal supply of water. Equilibrium will be established when the gradients of the two streams are essentially alike, though of course differences in rock character and structure on opposite sides of the block, as well as differences in the amount of water supplied and other factors, enter to complicate the process. The material worn from the blocks may be deposited in the valleys, which thus take on a level surface (Fig. 647).

The Wasatch Mountains as an Example. — The Wasatch Mountains, which, as already stated, form the eastern fault block that bounds the Great Basin, have a gentle slope toward the east for a distance of 15 to 20 miles. The western slope, the fault scarp, is an extremely abrupt one, elevations of 10,000 feet being attained within one or two miles of the western base, where the mountain rises abruptly from the broad flat plains of the Utah Basin. These plains are formed by an unknown thickness of alluvial deposits which cover the valley floor (Fig. 648). In spite of this difference of slope, the main crest of the mountains produced by erosion lies

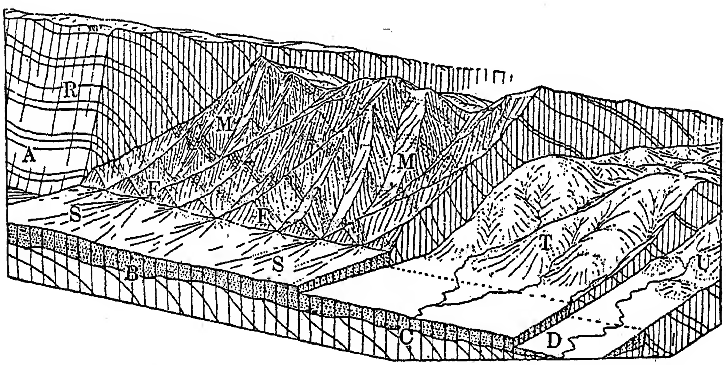


FIG. 648. — Diagram illustrating several stages in the development of the Wasatch Mountains from the original fault block (A) through rugged mountain topography (*B*); to subdued mature topography (*C*); and final obliteration (in the future) and formation of a peneplane (*D*). (After Davis. *Erklärende Beschreibung der Landformen*).

near the eastern border, and the westward flowing streams are generally from two to three times the length of the eastward flowing ones. Thus the divide has been pushed by erosion two thirds or more of the way across the original block. The various stages in dissection of the fault block are illustrated in the diagram (Fig. 648).

On the crystalline and metamorphic rocks of this block, peaks from 11,000 to 12,000 feet in height have been developed, and they have rugged pinnacle-like forms. On the slightly tilted sedimentary rocks, peaks of pyramidal outline with cliffs and slopes are developed. These erosion forms are not wholly due to river wear and weathering, for ice erosion has also played an important part in the higher regions. Below the level of glaciation, however, that is, in summits less than 9000 feet in height, the outlines are rounded and softened by heavy slopes of land waste.

The Sinai Type of Fault-Bounded Cuesta Block

A striking example of a block isolated by graben-faulting, but having otherwise the character of a normal cuesta, is seen in the Sinai Peninsula. This is of triangular outline, the apex being on the south, where two rift valleys converge, that of the Gulf of Suez on the west and that of the Gulf of Akaba, continued in the Vale of Araba and the Dead Sea, on the east. The apex of the peninsula is formed of a series of much dissected peaks of crystalline rocks (granite, porphyry, diorite, gneiss, etc.). Some of the peaks rise to considerable heights, notably the Jebel Mūsā group, which culminates in Mt. Catherine (8540 ft.). This, or the more isolated Mt. Serbāl (6750 ft.), is to be identified as Mt. Sinai or the "Mountain of the Law." North of this oldland mountain group lies a series of great valleys which represent the inner lowland, and from which arises on the north the great cuesta front of Jebel El-Tih, which attains a height of 3000 ft., and is much dissected into fantastic forms. (See map, Fig. 649.) This great cliff is formed of the cut edges of nearly horizontal strata, comprising chiefly the Nubian Sandstone, Cretaceous limestones, and, farther north, Tertiary Nummulitic limestones, the strata dipping at a gentle angle northward to the Mediterranean. From the summit of this cuesta-inface the surface descends northward in conformity with the dip of the strata for 250 kilometers (about 160 miles) passing beneath the level of the Mediterranean like a normal coastal plain. The surface thus has an average slope of less than 20 ft. per mile, and though under the prevailing climatic conditions it is partly a desert region (the desert El-Tih), it is dissected by wadis which form a consequent drainage system descending from near the south edge of the cuesta to the sea. On the east the edge of the cliff is dissected by numerous insequent valleys tributary to the Araba Graben. (See map, Fig. 649.)

The Rift Valley or Graben

The name Graben (ditch) has been given in Germany to valleys formed by the down-faulting of a long, narrow block of the earth's crust, and the typical example of such a Graben is the Rhine trough north of Mayence (Mainz) already described. The region was formerly a peneplane eroded on crystalline rocks, and upon this were deposited red sandstones and shales (Triassic with some

Permian), followed by shales (Lias) and limestone (Jurassic), which extended uninterruptedly across this region, uniting the remnants of these beds now seen on the one side in the cuestas of eastern France and on the other in the Swabian Alp, etc., of Germany. Later this region arose as an anticline or arch, the southward continuation of which was formed by a group of anticlines and synclines which constitute the Jura Mountains. (See Fig.

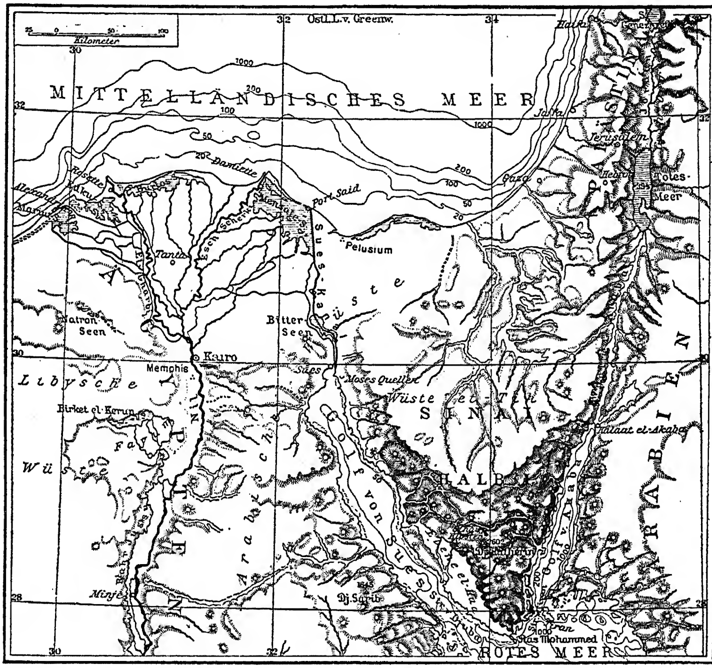


FIG. 649. — Topographic map of the Sinai Peninsula and the Nile region. (From Ratzel.)

552, p. 631.) At that time, or somewhat later, the center of the arch on the north collapsed, sinking down as a long, narrow block, bounded by a series of parallel fault planes on both sides (Fig. 650 *A*). Peneplanation of the region followed, and in this process the crystalline rock was uncovered in several places on each side of the fault block. This peneplanation appears to have extended widely over this entire region, being the extension of the peneplane which truncated the strata of the Paris Basin. We know that the faulting took place before the peneplanation, be-

cause upon the floor of the Rhine Graben are found the strata (Triassic and Jurassic) which this peneplanation removed on both sides, cutting, as we have seen, in places, even to the crystallines.

Conditions at the time of the completion of the peneplane were somewhat like those shown in the diagram Fig. 650 *B*. After the

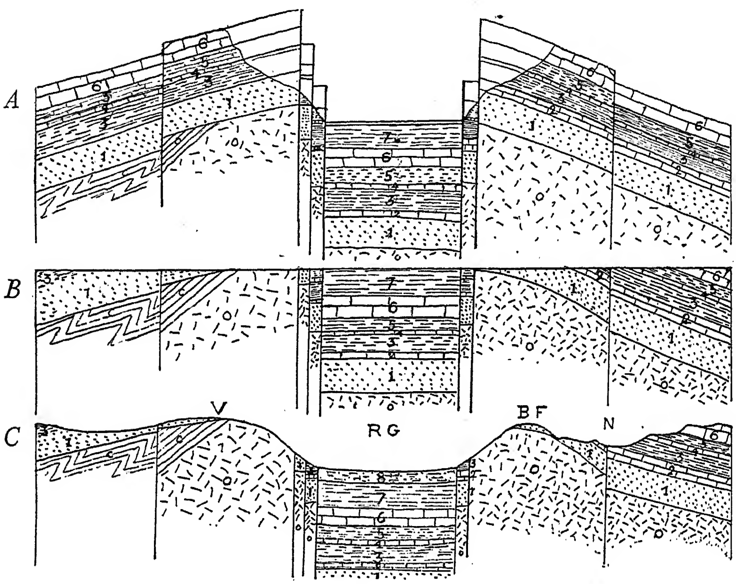


FIG. 650. — Diagrammatic sections to represent the development of the Rhine Graben and its present structural and topographic features. *A* (upper), conditions after the first faulting, which formed the original Graben which is occupied by the sea in which the Tertiary strata (7) were deposited; *B* (middle), the same region after peneplanation; *C* (lower), the same region after renewed faulting and dissection; *V*, Vosges Mountains; *R.G.*, Rhine Graben; *B.F.*, Black Forest (Schwarzwald); *N*, Neckar valley; *o*, ancient crystallines; *c*, folded Carbonic beds; 1. Buntsandstein (Triassic, including some Permian); 2. Muschelkalk; 3. Keuper; 4. Lias; 5. Dogger shales and sandstones; 6. Malm, forming the Swabian Alp; 7. Tertiary (chiefly Oligocene); 8. Quaternary and modern alluvium.

peneplanation, renewed faulting set in, the movements continuing in some places even to the present time. The northward continuation of the Graben was blocked by the outbreak of a series of volcanoes, especially between Darmstadt and Kassel, and in consequence the Rhine, which had begun to occupy this trough, had to cut its path across the slate mountains and so form its famed gorge (Fig. 601, p. 703). In the south, the uplifted sides of the

Graben carried the crystallines to a high altitude, and these constitute to-day the Vosges Mountains on the west and the Black Forest on the east. Because of the hard character of these rocks, they have resisted erosion and now constitute prominent barriers on both sides of the Rhine Graben. A steep fault scarp, somewhat modified by later erosion, faces the Rhine Valley on each side, while from the top of each range a gentle slope extends backward to the foot of the first cuesta formed by the erosion, in the second cycle, of the softer beds beneath the harder cliff-making limestones (Fig. 650 *C*).

Recent rift valleys of this type exist, as we have seen (Fig. 554, p. 632), in east Africa, where volcanic eruptions likewise have blocked the continuity of the valley in many places, with the formation of lakes, of which Tanganyika is one (Fig. 555, p. 633). The Palestine rift valley, occupied partly by the Dead Sea, the River Jordan, and the Sea of Galilee, and continued southward in the Gulf of Akabah, is also a very recent one. In this, erosion is apparently still in the first cycle, having modified only the sides of the trough to a certain extent (Fig. 649, p. 755). Among the minor erosion phenomena along the Dead Sea are the salt pillars carved from ancient salt beds exposed by the faulting, and one or another of which has been identified since time immemorial as the statue of Lot's wife.

Checker-board Fault Structure

Where a country is traversed by many parallel master joints arranged in two intersecting series, dislocation of the blocks thus produced, results in the elevation of some and the depression of others, the amounts being variable in the different blocks. Such a checker-board dislocation of a country produces a series of more or less rectangular elevated and depressed fields, and on these erosion will produce a most complex series of river systems. If such a region is finally peneplaned, a very complicated rock surface will result, some squares consisting of one kind, others of different material, and all abruptly bounded by fault lines. In the second cycle of erosion, the softer beds will be attacked and a complicated topography is produced.

Southern Sweden is one of the best known examples of this structure. Here one passes abruptly from rounded hills of crystal-

line rock to buttes or table mountains cut on horizontal strata, and from these to regions covered with more or less inclined strata, and on again to hills of crystalline rock, there being absolutely no regularity of structure. The geologist working in such a field passes abruptly from rocks of Archæan age to those of Mesozoic. These may in the next block be replaced by Cambrian and Ordovician strata, beyond which a block exposes Tertiary beds at the

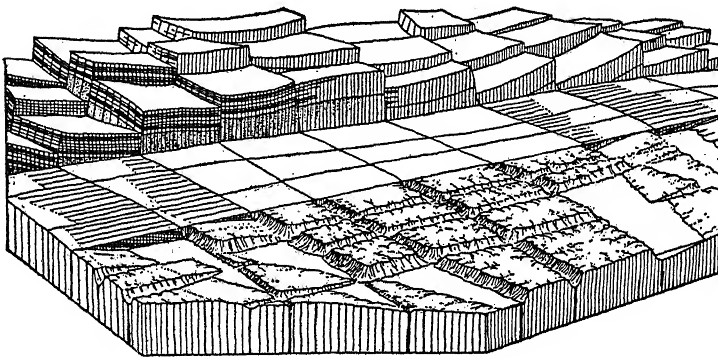


FIG. 651. — Diagram showing block faulting of the checkerboard type; peneplanation of the region, and the development of a complicated topography by erosion in the second cycle. Illustration of the geology of central Sweden. (After Davis.)

surface, and then follows perhaps one with Silurian strata. Along the fault lines, valleys are often carved, and some of these may be occupied by lakes. Constant diversity appears to be the keynote, not only of the rocks and rock structures, but of the topography as well (Fig. 651).

Fault-Line Valleys

When a country traversed by faults of some extent has become peneplaned during the first cycle of erosion, a valley may be cut by streams along the fault line during the succeeding cycle. For not only is the fault line one of weakness in the earth's crust, but along it are apt to be found many remnants of weaker strata which, being faulted below the level of peneplanation, escaped removal during the first cycle but are readily attacked in the second cycle. As a result, valleys will be formed which have no marked adjustment to the kinds of rocks, and which, moreover, may extend in a continuous manner for great distances. Such

a valley is the Great Glen which traverses the Scottish Highland region from Loch Linnhe on the southwest to the Moray Firth on the northeast, and which, on account of the succession of beautiful lochs situated along it, makes this not only the most picturesque but also the easiest line of travel across Scotland from Oban to Inverness.

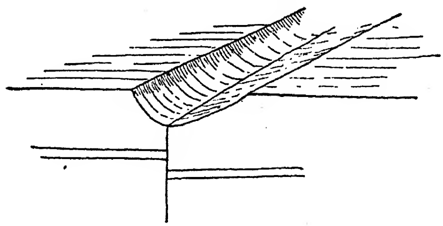


FIG. 652. — A fault-line valley. (From *Principles of Stratigraphy.*)

Such *fault-line valleys* must be distinguished from fault valleys or troughs, the latter representing purely a structural feature, the valley always being in the first cycle. The fault-line valley, on the other hand, is an erosion feature, often in a later cycle after peneplanation has destroyed the original fault topography (Fig. 652).

Renewal of Fault-Scarp Topography

If in a faulted region the original fault topography has been destroyed by peneplanation, erosion in the second cycle may renew the fault-scarp topography by removing the softer rock on one side of the fault and leaving the harder rock on the other side in relief. The scarp or cliff thus produced along the fault-line is called a *fault-line scarp*, in distinction from the *fault scarp* which is the original cliff due to dislocation. According to the nature of the strata uncovered on either side of the fault-line by peneplanation, the fault-line scarp may face in the same direction as the original fault scarp, that is, face the down-throw block, in which case it is called *resequent*, since it retakes a consequent position [re(con)sequent]. On the other hand, it may face in the opposite direction, *i.e.*, face the original upthrow block, if the strata exposed by peneplanation upon the surface of this block, prove to be the softer. In such a case, the fault-line scarp is said to be *obsequent*. Neither fault scarp nor fault-line scarp will long maintain its position along the fault-line, but erosion will progressively push them back until the cliff may be many miles from the fault-line, though essentially parallel to it. Such cliffs are characteristic topographical features of the plateau country west of the Rocky Mountains, though in most cases they have not weathered back very far from the fault plane.

Some Illustrations of Complicated River Erosion

We may here introduce a few typical examples of complexly adjusted rivers and the topographical features which accompany them, in order that the student may appreciate the interrelations of the various forces operative in producing a complex series of land forms. We will select the Niagara, the Genesee, and the Colorado rivers.

Niagara River and Falls

The Niagara River differs from the normal form of river, which we have been considering, in so many respects that it may be taken as the type of a special class, that of the spillway of one water body into another.

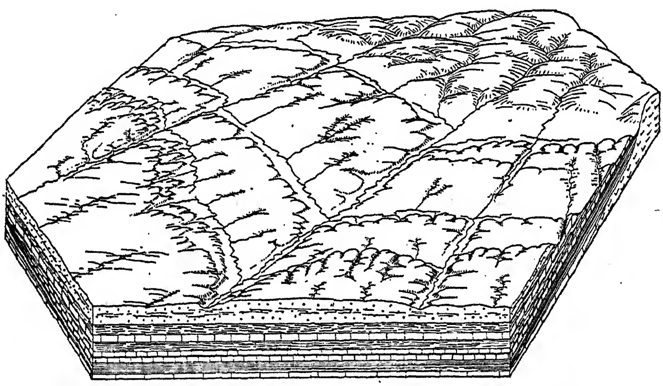


Fig. 653. — Block diagram illustrating the formation of three cuestas and lowlands by normal drainage on the peneplaned strata which surround the old Ontario dome on the south and west. Three principal streams are indicated, of which the middle one is the master stream (Dundas river). (Drawn by Mary Welleck.) See also maps, Figs. 617, 618, p. 727.

Pre-Niagara Topography. — Before Niagara River came into existence, the region was the site of normal dissection of part of a low dome that had been peneplaned, as has previously been outlined (p. 725). As a result, three lowlands and cuestas had come into existence, of which the northernmost was the most profound and the middle one the shallowest (Fig. 653). These three cuestas are formed by the three resistant formations of the region, and are, respectively, the Niagara cuesta (Fig. 654, *a*), the Onondaga cuesta (*b*), and the Portage-Chemung cuesta or front of the Alleghany

plateau (c), while the lowlands in front of these are the Ontario lowland (A), the Salina lowland (B), and the Erie lowland (C). The peneplane is indicated by the beveled surfaces of the Niagara and Onondaga limestones at the edges of the respective cuestas, and the summit elevation of the Alleghany front south of Buffalo. When these points are connected by a line which restores the peneplane surface, it is seen that this old surface now rises to the south, and this indicates that the peneplane has been tilted to the north with possibly some warping which carried the southern region to greater altitudes. Such tilting occurred, however, only after the cuesta and lowland topography had been etched out of the hard and soft strata, respectively, by a revival of the consequent and subsequent drainage from the old Ontario dome toward the southwest (p. 726). Indeed, this tilting appears to have been due to the depression of the land on the north during, and prob-

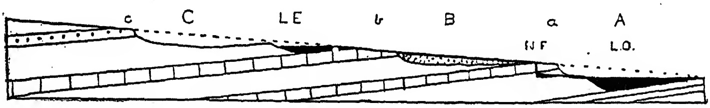


FIG. 654. — North-south section across western New York, showing the three cuestas and lowlands and the tilting of the peneplane. a, Niagara cuesta; b, Onondaga cuesta; c, Portage-Chemung cuesta; A, Ontario lowland; B, Salina lowland; C, Erie lowland; *LO*, Lake Ontario; *NF*, Niagara Falls; *LE*, Lake Erie.

ably because of, the accumulation of the continental ice sheet of Pleistocene time. As a further result of this northward depression, the floor on the Ontario lowland was carried several hundred feet below the present sea-level, from its position some distance above that at the time of its formation by river erosion (Fig. 654).

As these various lowlands extend in a direction at right angles to that of the movement of the great ice sheet in Pleistocene time, they suffered no appreciable deepening, though the tops of the cuestas may, in some cases, have been planed down to a slight extent.

In addition to the depression of the country on the north, the valley of the master consequent stream had been filled by glacial drift, and the same thing happened to the shallow Salina lowland. Thus, with the outlet of the inner lowland choked by drift, and the actual slope of the country reversed by depression, the Ontario lowland became a circumscribed basin and was filled with water

up to the level of the lowest point in the rim, which is at present at the Thousand Islands, a region that was, in the days of former great elevation, the head of the St. Lawrence River and the divide between it and a westward flowing stream which joined the subse-

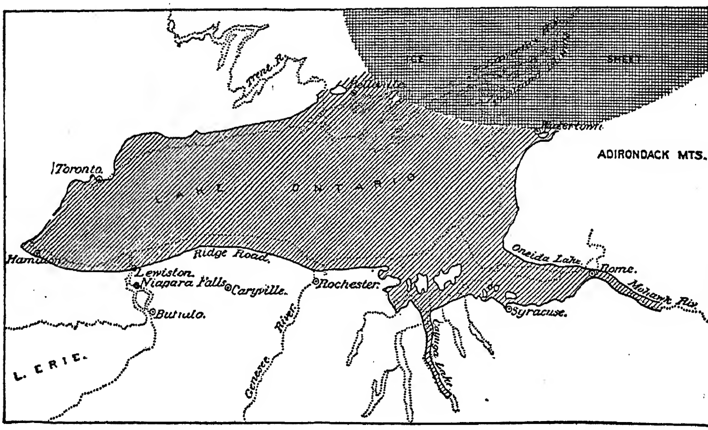


FIG. 655. — Map of Lake Iroquois, with the modern outlines of Lake Ontario, etc., shown in dotted lines. (After Gilbert.)

quent by which the Ontario lowland was carved (see maps, Figs. 617 and 618, p. 727). Before the present St. Lawrence outlet came into action, however, the waters of the lake in the Ontario lowland overflowed along the line of the old Ontario River and across the divide at Little Falls into the Mohawk and Hudson. This was

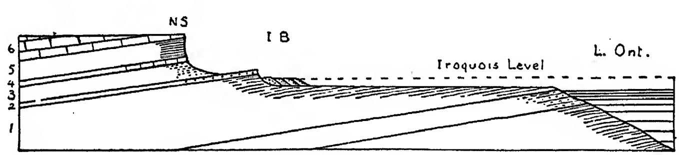


FIG. 656. — The edge of the Niagara escarpment. *NS*, showing the position of the ancient Iroquois Beach (*IB*) and the relation of the Iroquois level to that of Lake Ontario.

necessitated by the fact that a part of the great ice sheet still lingered in the region of the Thousand Islands and so blocked that outlet (Fig. 655). As a result, the level of the lake, called Lake Iroquois, stood higher than the present Ontario level and extended farther over the flat terrace which lies between the Niagara escarpment and the submerged part of the cuesta. The

ancient shore-line is distinctly marked by one or more abandoned beaches, which can be traced along the southern border of Lake Ontario but distant from it some miles (Fig. 656). The principal one is followed by the so-called Ridge Road.

Because of the northward tilting of the land and the choking of the old outlets, the Erie lowland also was transformed into a lake basin, its level being likewise determined by the lowest place of outlet in its rim, which happened to be across the Onondaga cuesta where Buffalo now stands. Spilling over at this point, the waters took their course across the country in a northward direction, this being the only avenue of escape open to them, until they reached the edge of the Niagara escarpment where Lewiston stands to-day, and there fell over it as the newborn Niagara Falls. That no fall or only a slight one came into existence over the Onondaga cuesta was due to the filling of the lowland in front of it by glacial drift, and also because at the point of overflow there appears to have been an old notch cut in the escarpment by some obsequent stream during the period of normal valley erosion.

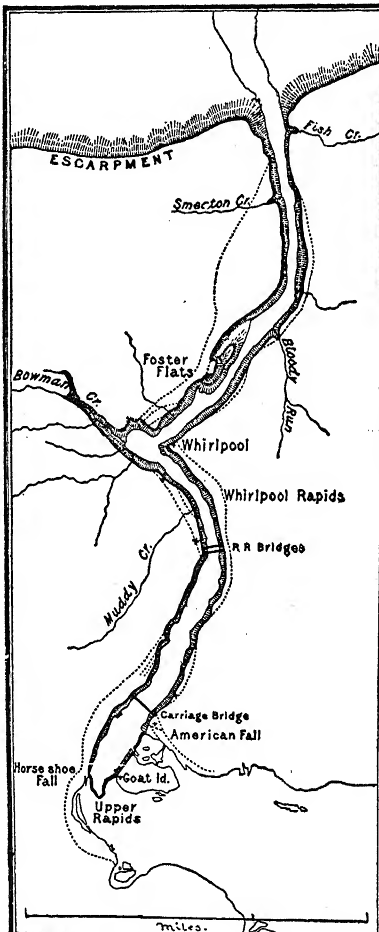


FIG. 657.—Map of the Niagara Gorge, showing variable course and physical features. (After Gilbert.) Old river banks are shown by dotted lines; shell localities, by crosses.

Peculiar Course of Niagara River.—If we examine the course of Niagara River, we find certain peculiarities, especially repeated

changes in direction, unlike what we might expect in a normal spill-over from one water body to another across a comparatively level plain (Fig. 657). From its head at Buffalo, northward, the river is a broad placid stream dividing into two arms which reunite and enclose a large flat island called Grand Island. Beyond this it turns almost due westward and soon becomes a turbulent, though still very broad, stream in which no boat can make headway. Then it plunges over a succession of low limestone ledges as a magnificent series of rapids until it has descended about 50 feet vertically, when it reaches the present falls, of which there are two, the American, parallel to the line of rapids, and the Horseshoe

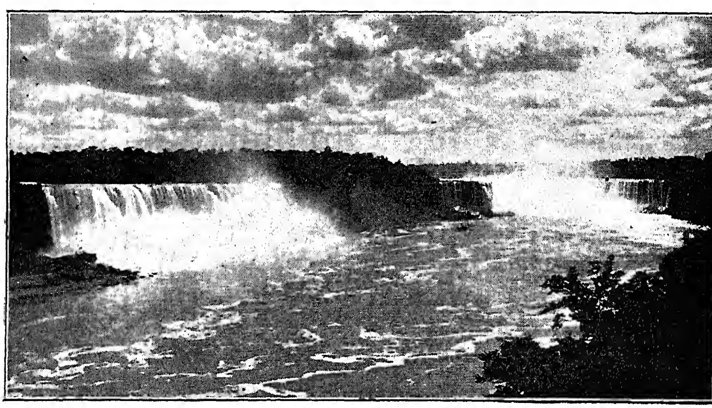


FIG. 658. — Niagara Falls.

Falls, opening in a curve almost due north. Between the two lies Goat Island, a drift-covered rock mass which rises nearly to the level of the river above the upper rapids (Fig. 658).

From the foot of the Horseshoe Falls the gorge extends in a direction somewhat east of north for about three miles, and it is virtually over the side of this gorge that the American cataract falls. The width of this part of the chasm varies from 1250 to 1700 feet at the top, its banks being for the most part nearly vertical. The depth to water-level is nearly 200 feet, and the water itself is from 150 to 200 feet deep.

Just before it passes under the railroad bridge at Clifton, the gorge suddenly turns to the northwest, making almost a right angle. It also contracts to a width of about 700 or 750 feet at the top and 550 feet at the water-line, and the water becomes only

about 35 feet deep. This is the beginning of the Whirlpool Rapids, the waters here tumbling over each other with indescribable fury and descending 50 feet in the space of less than a mile (Fig. 659). This portion of the gorge ends at the Whirlpool, a deep circular basin a thousand feet or more in diameter which has a depth of water ranging from 150 to 200 feet (Fig. 660). At the great swollen elbow of the Whirlpool, the gorge makes another right-angled turn, extending northeast for nearly two miles. This part is again a wide gorge, the width at the top varying from 1300 to 1700 feet, though it is less at the water-line. The depth of water is, however, not great, being at the Whirlpool outlet 50 feet and ranging from 35 to 70 feet in other parts. In this portion of the gorge on the Canadian side is an interesting table rock, known as Foster's Flats, to which reference will be made again. At the end of this part of its course, the river turns due north, retaining about the same width to the edge of the escarpment at Lewiston, and thence continuing in the same direction as a broad navigable stream with relatively low banks for seven miles more to Lake Ontario.

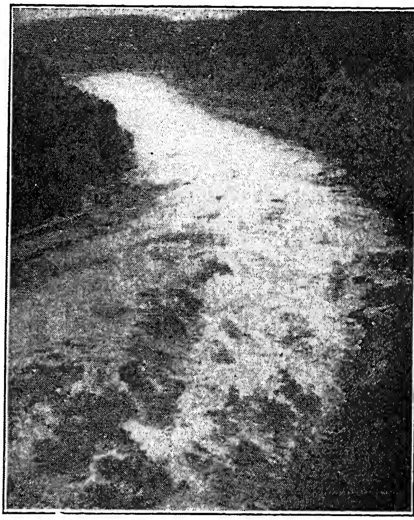


Fig. 659. — The Whirlpool Rapids gorge at Niagara. (From Grabau, *Geology of Niagara Falls*, N. Y. State Educational Department.)

The three bends in the gorge, together with the changing width and depth (Fig. 661), are its most striking feature, while the sudden bend in the river at the Horseshoe Falls is another feature of significance. Tracing the lower part of the gorge, which extends due north, southward to the bend, we find it aligned with a shallow trench in the upland extending for a mile or more due southward and occupied by a small stream, the Bloody Run, famous as the scene of an Indian massacre during the wars of 1763, and which forms the chasm of the Devil's Hole where it enters the present

gorge. The valley of this stream is readily recognized as a preglacial one, and it appears that it is the upper part of the valley of an obsequent stream which flowed over the edge of the escarp-

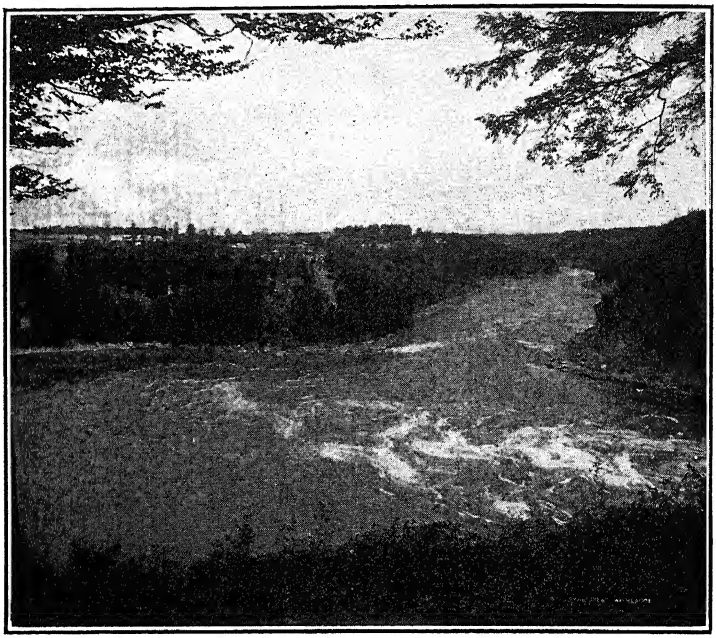


FIG. 660. — The Whirlpool in Niagara gorge. (From Grabau, *Geology of Niagara Falls*. Courtesy N. Y. State Educational Department.)

ment during the earlier period of normal erosion and long before Niagara came into existence (Fig. 662). Thus the course of the lower gorge and that of the river beyond to Lake Ontario appears to have been predetermined by the cutting of a shallow obsequent

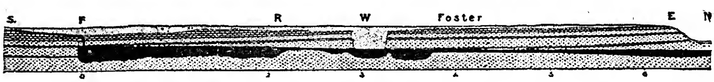


FIG. 661. — Longitudinal section of Niagara gorge from the Falls (F) to Queenston Heights (E) showing the west bank and the depth of water (in black) at the several points, W, Whirlpool; R, railroad bridges. (After Gilbert.)

valley in the surface of the cuesta, though it probably was not cut back very far from the edge of the escarpment at Lewiston.

The gorge of the Whirlpool Rapids south of the Whirlpool presents another such case. As noted, this extends almost due

northwest to the Whirlpool. An examination of the northwestern border of the Whirlpool discloses the fact that it is formed by glacial drift instead of rock, and a series of borings has shown that an old drift-filled gorge extends from the Whirlpool northwestward to the edge of the Niagara escarpment at St. Davids, gradually widening in this direction (Fig. 662). Beyond St. Davids it has not been traced, but without doubt it extends to Lake Ontario. This ancient St. Davids Gorge appears to represent another obsequent stream which had cut back from the edge of the cuesta, probably, to the head of the Whirlpool Rapids gorge at the Clifton railroad

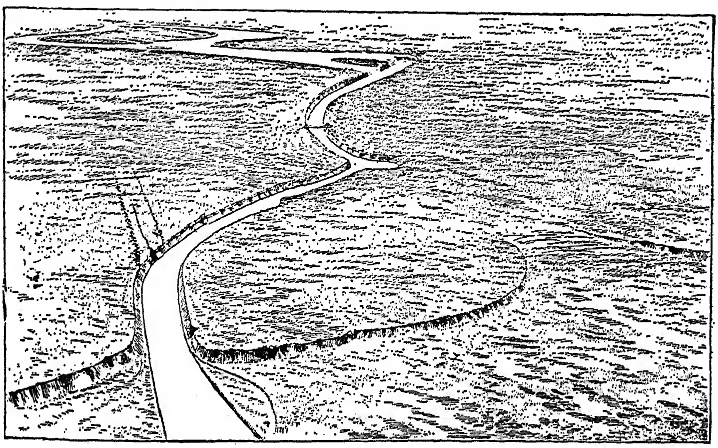


FIG. 662. — Bird's-eye view of Niagara gorge, showing the course of the river, the falls, the railroad bridges, Whirlpool, location of Foster's Flats, escarpments at Queenston, pre-glacial valley of Bloody Run, and flaring mouth of pre-glacial St. Davids Gorge. (Modified after Gilbert.)

bridge. At the inlet of the Whirlpool, where the water is less than 50 feet deep, the gorge is crossed by a heavy bed of white sandstone called the Whirlpool sandstone, and just beyond this the depth of the water becomes 150 to 200 feet. Evidently there was here a waterfall of that height in the ancient obsequent river determined by the presence of this bed of sandstone.

These facts adequately account for the direction of the gorge of the Whirlpool Rapids and for its narrowness and shallowness as compared with other parts. Evidently it was largely drift-filled to its head when the overflow from Lake Erie was directed into it, and followed it for some distance before the drift-filling became so high that the waters were forced to spill over the side of

the shallow channel and find their way across the country to another ancient and partly drift-filled obsequent valley. The following section (*AB*, Fig. 663) gives the approximate profile of this old St. Davids valley. When the falls had cut back nearly to the site of the Whirlpool (section *CD*, Fig. 663) only a narrow rock wall upheld the drift-filling of the Whirlpool and Whirlpool Rapids Gorge, and when this barrier broke the drift was quickly cleared out and the falls became suddenly transferred to near the head of the Whirlpool Rapids Gorge.

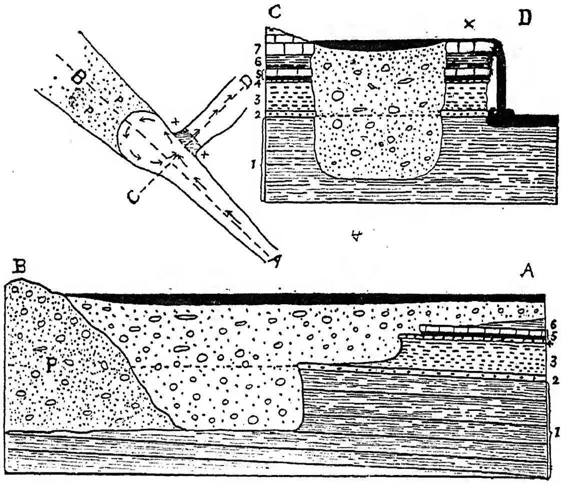


FIG. 663. — Sections of the Whirlpool at Niagara before the former drift-filling was cleared out by the river. 1, Queenston shales; 2, Whirlpool sandstone; 3, Medina shales and sandstones; 4, Thorold quartzite; 5, Clinton shale and limestone; 6, Rochester shale; 7, Lockport dolomite; *x*, the narrow rock barrier northeast of the St. Davids Gorge, the destruction of which caused the sudden clearing of drift from the Whirlpool and the transference of the falls for some distance upstream.

The upper portion of the gorge, for three miles down stream from the falls, was also directed by a shallow valley in the upland across which the Erie waters spilled. This appears to have been the valley of an old consequent stream originally flowing in a southwesterly direction, but with the present slope reversed owing to tilting and to partial drift-filling. It was cut into the upland to a depth not much over 50 feet, but this was sufficient to guide the waters as they spilled into it. The western side of this valley is seen in the cliff opposite the Horseshoe Falls on the Canadian side,

and the eastern in the rapids above the falls, which here extend continuously across the river.

We thus see that the course of the Niagara River is due to the spilling over of the waters from one ancient channel to another, and that the falls cut back along these channels, sometimes as a single fall, at others probably as a succession of falls, with a sudden transference upstream for about a mile when the barrier which held in the drift filling of the upper end of the St. Davids Gorge (Whirlpool Rapids Gorge) was broken and the drift cleared from this part of the old channel.

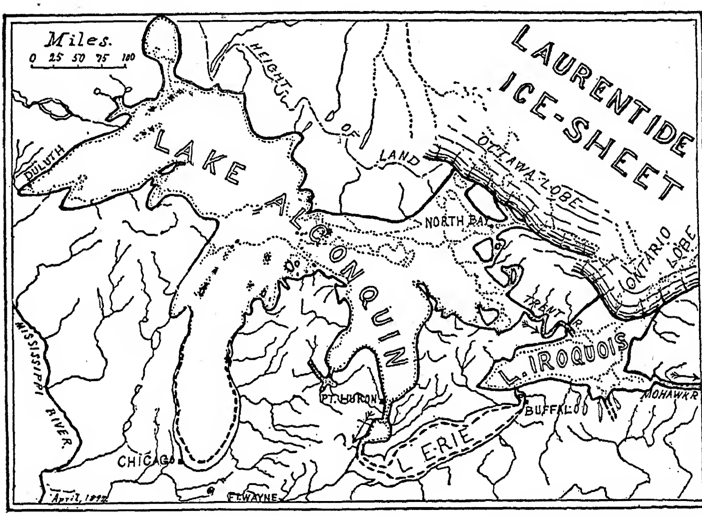


Fig. 664. — Map of glacial Lake Algonquin and the discharge by the Trent river. (After Taylor.)

There are some other larger geographic factors which must be taken into account in the history of Niagara. Thus it has been clearly shown that, for a time at least, the waters of the upper Great Lakes discharged, not as they do now into Lake Erie by way of the Detroit River and thence over Niagara Falls, but by a more direct route across Ontario along a valley now occupied by the Trent River (Fig. 664). This meant, of course, that the water flowing over Niagara was only the spill-over from the much smaller Lake Erie of that time, and therefore the Falls were not able to cut so deep and broad a gorge as they do to-day, nor retreat at so rapid a rate. It has been held that during the existence of these

conditions the shallower part of the gorge north of the Whirlpool was cut. Still later, when the ice had melted away from the St. Lawrence outlet, which was then even lower than at present, owing to the greater depression of the land, and was, moreover, because of this depression, probably flooded by water entering from the sea (Fig. 665), the upper Great Lakes discharged directly to the St. Lawrence or the sea which occupied its valley, along a course now partly occupied by the Ottawa River. This still left the Niagara only the drainage from Lake Erie, and it is held by some that during this period the Whirlpool Rapids Gorge was cut, or

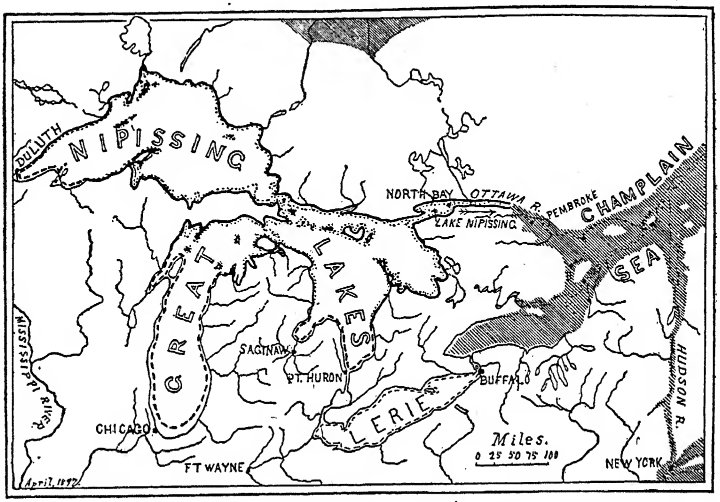


FIG. 665. — Map of the Nipissing Great Lakes, and the marine submergence of the Champlain and Ontario valleys. The outlet of the Great Lakes is by the Ottawa River. (After Taylor.)

at least deepened, and that because of the small quantity of water carried over the falls, this deepening and widening was much less than it would have been with the present volume of water.

After this period, the land in the north began to recover from its depression, and as we have seen (p. 695) may still be slowly rising, as indicated by the abandoned beaches in the north and the encroachment of the waters of the lakes on the south shores. When the tilting back toward the original position had progressed so far that the upper Great Lakes began to spill over by way of the Detroit River into Lake Erie, Niagara was forced to carry out the combined drainage of these lakes and assumed its present volume

of 22,440,000 cubic feet or more than 7,000,000 tons per minute. Since this time it has cut its broad deep gorge from the railroad bridge to the present Falls. This cutting, judging by the measured rate of retreat during the last three quarters of a century, must have taken about 3000 years. Thus the beginning of the great cataract about three miles north of its present site, dates back to about the eleventh century B.C., or to about "300 years before the time of Romulus, or to the reign of King David at Jerusalem" (Hitchcock). How long it took to cut the other parts of the gorge is more difficult to determine, because of the variable factors above referred to. It is probably safe to say that it was at least 50,000 years ago when the falls began near Lewiston, and it may have been several hundred thousand years ago.

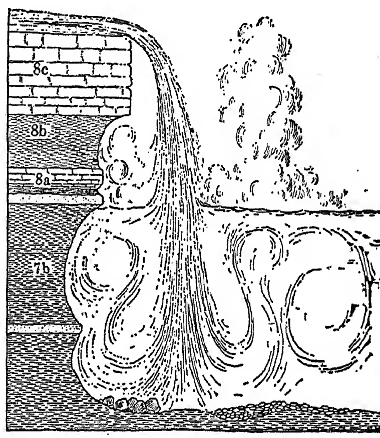


FIG. 666. — Section of the Horseshoe Falls, Niagara, to show the depth of water below the falls and the arrangement of the strata. 7 *b*, Medina sandstones and shales with Whirlpool sandstone at base (resting on Queenston shales) and Thorold quartzite above; 8 *a*, Clinton shale and limestones; 8 *b*, Rochester shale; 8 *c*, Lockport dolomite. (After Gilbert.)

Mode of Cutting of Niagara Falls. — Niagara River carries no sediment. Where it leaves Lake Erie the water is so pure that the intake of the water supply of the city of Buffalo is located at that point. What sediment is brought in by lateral streams or picked off the bank is dropped in the quieter water long before the falls are reached, over which the water passes as a pure stream. The erosion accomplished by the cataract is entirely due to undermining by spray and to the force of the falling water. The greatest amount of water passes over the Horseshoe Falls, and the section here is shown in the above diagram (Fig. 666). It will be observed that a heavy bed of limestone (about 80 feet thick) (8*c*) caps the cliff and is underlain by softer shales with some limestone and sandstone layers. It is these softer beds which are slowly removed by the water and spray driven against their edges and by the quarrying activity of the

frost in winter. Thus the limestone ledge comes to overhang more and more, and eventually it breaks down from its own weight and that of the water above it. Thus the gorge is lengthened by periodic rock falls. The fallen blocks are broken and ground up by the enormous force of the descending water, and in this process they dig into the soft red shales and sandstones of the river bottom (7*b*), thus producing a depth of water approaching 200 feet. In other words, the force of the plunging water is so great that the gorge-cutting goes on for a depth of 200 feet below the level of the river in front of the falls, producing a "plunge basin" of unusual magnitude and depth.

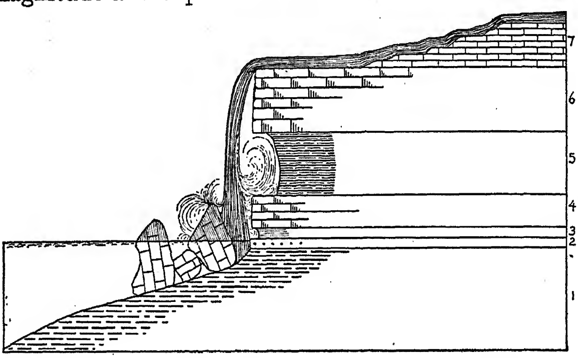


FIG. 667. — Section of the American Falls at Niagara; the rapids above the Falls are formed by the thin-bedded Guelph dolomites (7); the edge of the falls is formed by the Lockport dolomite (6); the Cave of the Winds is cut by the spray from the Rochester shale (5); and its floor is formed by the Clinton limestone (4); beneath this lie the Clinton shale (3), the Thorold quartzite (2), and the Medina sandstones and shales (1). In front of the falls lie the larger blocks of Lockport dolomite, broken from the edge of the falls.

The American Falls, on the other hand, having so much less water, are not able to cut such a plunge basin. Indeed, the water is unable to move or destroy the larger fallen blocks of limestone, and so the foot of these falls, as seen from the Canadian side, is lined by rows of such large blocks (Fig. 349, p. 418). The section of these falls is shown in the preceding diagram (Fig. 667). Here too, the soft shale (Rochester) immediately below the capping limestone is removed by spray and frost, so that the limestone overhangs. Another limestone series (Clinton), about 40 feet thick, lies beneath this shale, and this is not destroyed by the spray. Thus the "Cave of the Winds" is produced, the floor of which is formed by the lower (Clinton) limestone and the roof by the upper (Lock-

port) limestones, the cave itself being due to the retreating face of the shale (Rochester), which is about 80 feet thick.

Unequal Retreat of the Falls. — It is readily seen that because of the greater amount of water which flows over the Horseshoe Falls, these retreat more rapidly than do the American Falls. Between the years 1842 and 1890, the measured retreat, according to sur-

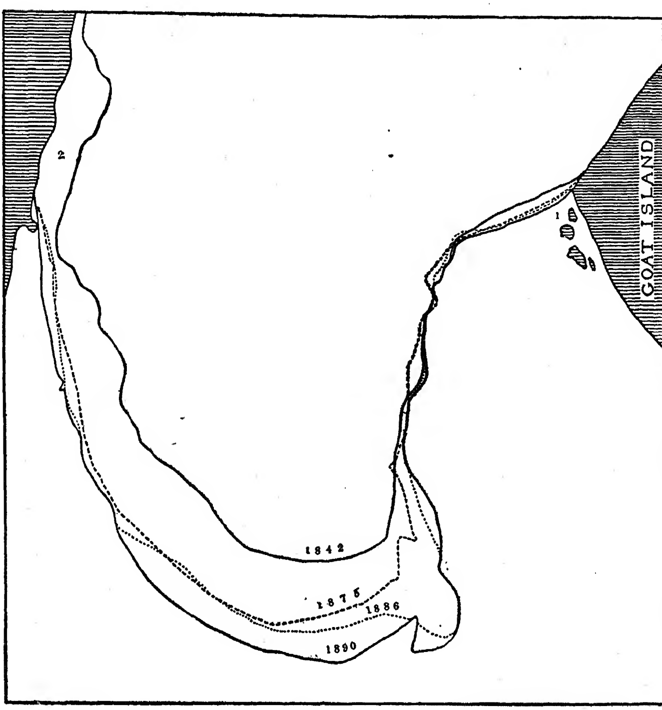


Fig. 668. — Successive crest lines of the Horseshoe Falls, Niagara, from 1842 to 1890. 1, Terrapin rocks; 2, Former Table Rock. (After Grabau, *Geology of Niagara Falls.*)

veys (Fig. 668), when distributed over the entire falls, gave for the American Falls a mean total recession of 30.75 feet, or a mean annual recession of 0.64 feet, and for the Horseshoe Falls a mean total recession of 104.51 feet, or a mean annual recession of 2.18 feet. Figured in area, this gives a removal of rock surface from the edge of the falls between these years of 0.755 acres for the American and 6.32 acres for the Horseshoe Falls. The greater volume of water is due, of course, to the fact that the Horseshoe

Falls lie in the path of the main current of the river which, striking the left bank above the falls, is deflected so as to carry its full measure over the Horseshoe Falls. The outline of the crest of the American Falls, as it appeared at the beginning of this century, is shown in the photograph (Fig. 669) from Goat Island.

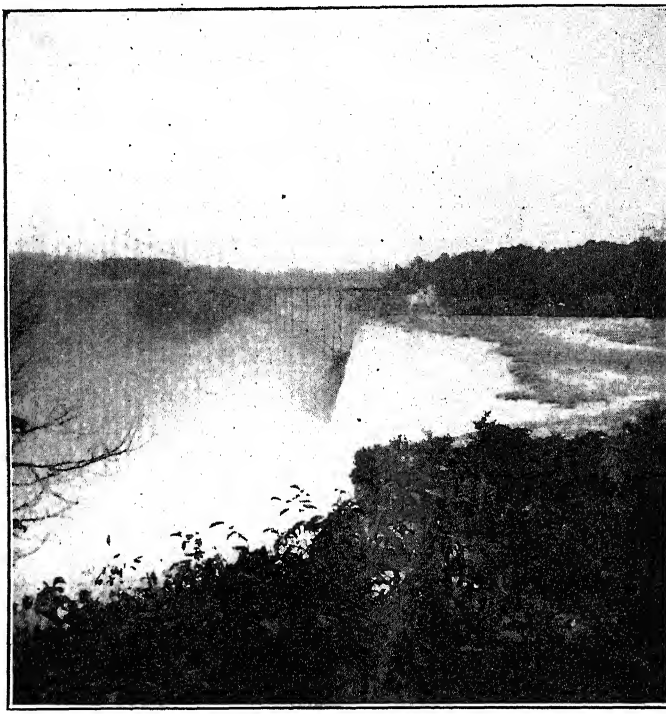


Fig. 669. — Crest of American Falls at Niagara, as seen from Goat Island in 1911, showing irregular recession by the fall of large blocks which have become undermined. (Photo by author.) (See also Fig. 349, p. 418.)

It is easy to see that when the Horseshoe Falls have retreated to beyond the head of Goat Island, the American Falls will become entirely dry. Such an event has happened once before in that part of the gorge which lies below the Whirlpool. Only here, because the bend at the Whirlpool was a sharper one, the main current was thrown over to the right side, and this side was therefore deepened. An abandoned platform, once the site of a fall similar to the American Falls, is now seen on the Canadian side, forming Foster's Flats (Ongiara Park) (Fig. 670). At the foot of

the cliff over which the cataract once fell are found huge blocks of limestone similar to those seen at the foot of the present American Falls, and in some of these blocks the falling waters have bored

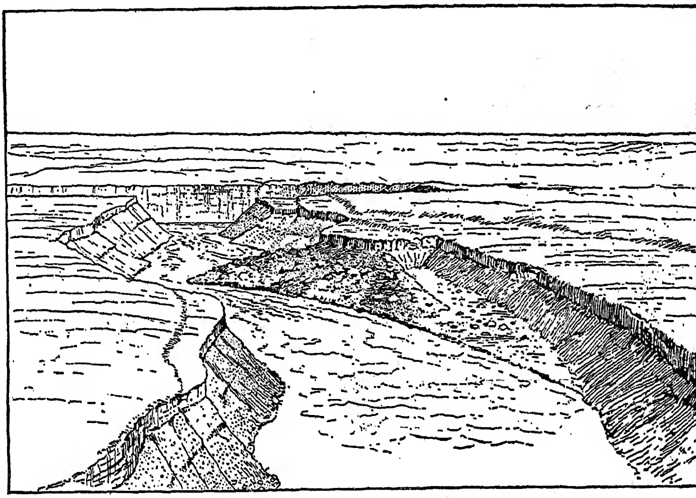


Fig. 670. — View of Niagara Glen or Foster's Flats looking south. Forests omitted. (After Gilbert.) This is the site of a former fall.

large pot-holes. This platform and its cliffs present precisely what will be seen in the American Falls when its waters are drawn off by the retreating Horseshoe several thousand years from now, or by man in the less distant future.

The Genesee River

As a second example of a complicated river history we will select the Genesee River, which traverses New York state from south to north, rising in the uplands of the Alleghany Plateau in Pennsylvania and ending in Lake Ontario north of Rochester, New York.

Preglacial Character. — The Genesee River lies in a region characterized by ancient valleys formed during the period of normal river erosion on the peneplaned strata which flank the Ontario Dome on the south. The erosion, which occurred in Tertiary time, resulted in the formation of numerous consequent valleys with subsequent branches. Many of the consequents were beheaded in the deepening of the Ontario lowland by the subsequent tributary to the master stream of the region (see map, Fig. 618, p. 727). The

map (Fig. 671) shows the location of several of these ancient valleys which are concerned in the history of this river. The principal ones are the Dansville Valley on the east with several tributaries, the upper Genesee Valley, and the Oatka Valley with the Dale Valley as a tributary. The largest of these is the Dansville Valley, which near Dansville is about a thousand feet deep and from two to

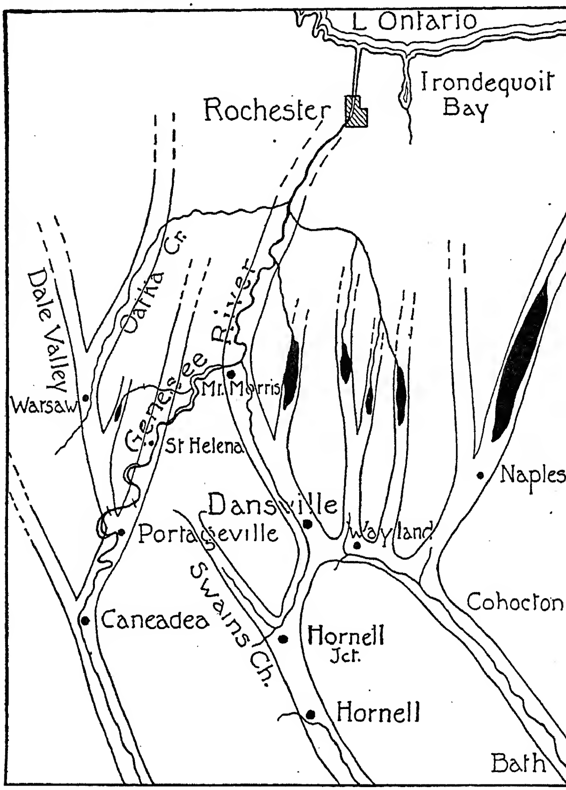


FIG. 671. — Map of the Genesee River country; showing old valleys and modern drainage. Modern lakes in solid black.

three miles wide. Traced southward, it becomes merged with other ancient valleys, and it is possible to trace the entire drainage system to the Susquehanna. But the most significant feature of the system is that the Dansville Valley north of that town is much deeper than the valley which continues the drainage system southward. Indeed, south of Dansville, the rock floor of the valley rises very rapidly for several hundred feet until it reaches the ele-

vation of the rock floor of the more southerly valleys. This is illustrated in the following diagram (Fig. 672), which shows the appearance of the valleys. The contrast would be greater if all the drift and other unconsolidated deposits were removed. This relationship is most readily explained by regarding the Dansville Valley as overdeepened by ice-erosion during the period when the great Pleistocene ice sheet was still in active motion in this region. Corroboration of this hypothesis is furnished by the form of the Dansville Valley, the sides of which above Dansville are much steeper than is characteristic of a mature valley due to normal river erosion and weathering in rocks of such soft nature. Rocky

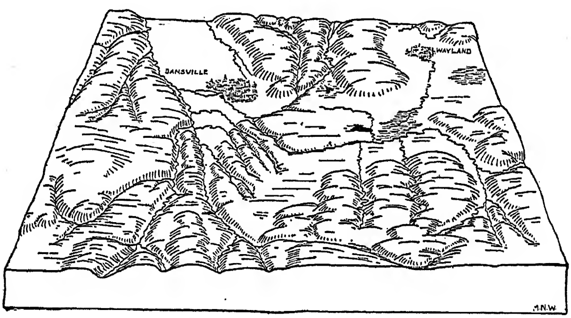


FIG. 672. — Diagram illustrating the relation of the Dansville to the Wayland Valleys. The floor of the Wayland Valley at Wayland has an elevation of 1372 feet. Its continuation on the extreme left hand of the diagram is 1300 feet. The elevation of the Dansville Valley at Dansville is 700 feet. Both valleys are partly filled by drift. The streams which dissect the Wayland Valley have cut narrow gorges in the rock bottom. (Drawn by Mary Welleck.)

spurs on the valley side have been truncated, a very characteristic feature of glacial erosion (see p. 799), and finally, a vast amount of morainal material dug up from this valley has been deposited in the valley south of Dansville and in the others which continue southward from this, such deposition being largely due to the waters from the melting ice. This is shown by the fact that the drift-covering of the valley-floor presents the stratification and surface characters of river-laid deposits.

The other north-south valleys have also been deepened by glacial erosion, but not to the same extent. This is well illustrated by the Oatka Valley, the floor of which lies more than 100 feet below that of the undeepened Dale Valley which joins it at Warsaw. Formerly the floor of the Dale Valley joined the

Oatka at grade, that is, the two levels were essentially in accord. To-day the point of junction is marked by a cliff of rock and a descent to the level of the Oatka Valley, which is here

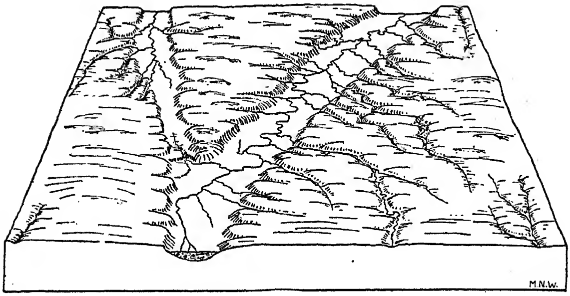


Fig. 673. — Diagram showing the junction of the Oatka and Dale Valleys near Warsaw. The Dale is a hanging valley on the side of the over-deepened Oatka. (Drawn by Mary Welleck.)

filled by more than 100 feet of alluvial material deposited upon it after the overdeepening. Thus the Dale Valley is a hanging valley on the side of the Oatka Valley, a type characteristic of glaciated regions (see p. 801). This is illustrated in the diagram, Fig. 673. The sides of the Oatka Valley are, moreover, steepened and its spurs are truncated. The overdeepening continues for some distance south of the town of Warsaw, and beyond that are heavy morainal deposits composed in part, at least, of the material scraped by the ice from the Oatka Valley. This moraine crosses the line of junction of the Oatka with the ancient Genesee Valley and com-

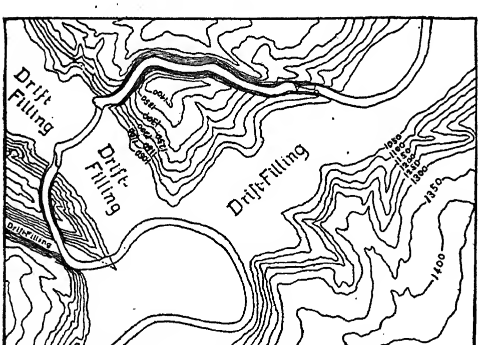


Fig. 674. — Map of the junction of the ancient valleys, now partly drift-filled, in the Portageville region, showing the approximate character of the valleys before they became modified by glacial erosion; the course of the modern Genesee with its gorges and falls is represented.

pletely divides this valley into two parts by a huge dam of drift at Portageville (Fig. 674).

Post-Glacial Development. — The subsequent history of the region was somewhat as follows. The land, it will be remembered, had been depressed on the north, so that the slopes of the valleys, which formerly were southward, now descended to the north. For a time, the Ontario Valley was occupied by ice, blocking the outlets to the east. This resulted in the damming of all the north-south valleys and their conversion into lakes up to the lowest point of outlet on the south, since drainage to the north was prevented by the ice. The outlets and levels of practically all of these lakes have been traced with considerable detail. When the outlet of the Ontario waters into the Mohawk (Rome outlet) was uncovered by the melting of the ice, the waters were lowered to the level of Lake Iroquois (p. 762), and, as will be recalled, the birth of Niagara took place. This resulted also in the draining of the Dansville and Oatka Valleys, but the upper Genesee Valley, being dammed by heavy moraines at Portageville, remained a lake. Instead of southward drainage, however, the overflow of this lake took place northward at a lower level, and thus was born the modern Genesee (Fig. 675). The overflow of the waters of the lake occurred on the west, then they turned north through a depression in the moraine, crossed the buried valley of the Oatka above its junction with the

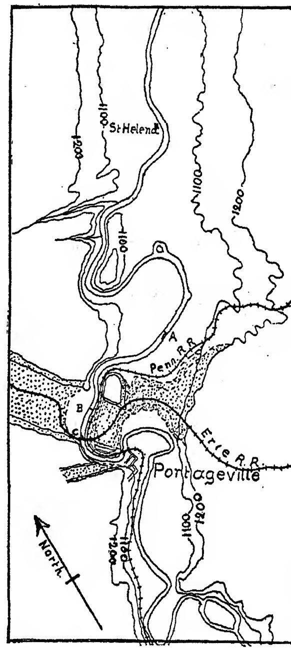


Fig. 675. — Map of the Genesee River from south of Portageville to about 9 miles south of Mt. Morris. The 1100 and 1200 foot contours represent the rock topography. The broken contour lines represent the same elevations on the drift filling. Note the broad and regular character of the old valley north and south of St. Helena. This has been glaciated. The valley south of Portageville shows rocky spurs and has been less glaciated. The modern stream has cut a narrow gorge in the bottom of the St. Helena valley as shown in the cross section near St. Helena, given in Fig. 683, p. 783. Drift fillings of old valleys dotted. *A*, Lower Falls, 70 ft.; *B*, Middle Falls, 107 ft.; *C*, Upper Falls, 71 ft.

old Genesee Valley, and finally spilled into the northern part of the old Genesee Valley which had been separated from the southern part by the heavy Portageville moraine. The new river was prevented from following this valley to Lake Ontario (Iroquois) by other heavy morainal material, and so the waters spilled over the side and flowed across the plateau surface to the Dansville Valley, plunging into it over the rocky side of that valley at the site of the modern town of Mt. Morris, and thence continuing for 60 miles more to the Lake, before reaching which, however, they had to descend over the exposed part of the inface of the Niagara cuesta, *i.e.*, the Niagara escarpment (Fig. 679, A).

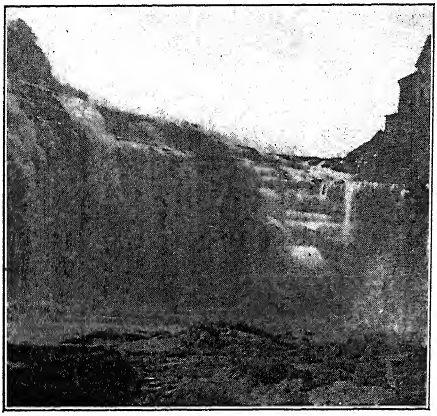


FIG. 676. — The lower falls of the Genesee at Rochester — over the upper hard Medina (Thorold) sandstone. (Photo by author.)

Gorge cutting by retreating waterfalls began at two points and occurred simultaneously with the cutting of the Niagara gorge farther west. One gorge was cut by the new Genesee from the Niagara escarpment southward, and the other from Mt. Morris southwestward. In the cutting of the gorge through the Niagara escarpment three hard layers were discovered, the lowest a white quartzite (Thorold) overlying softer red sandstones (Medina), the next a heavy limestone (Clinton) overlying shales, and the third another limestone (Lockport) overlying a still heavier shale bed (Rochester). These,

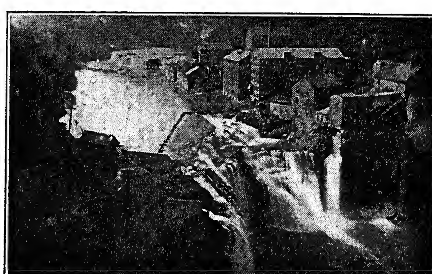


FIG. 677. — The lower and middle falls of the Genesee River at Rochester, the latter over Clinton limestones. (Photo by the author.)

it will be observed, are the same beds as those the Niagara River had to cut through, but because that river had so much more water, it has long since accomplished this cutting process and is now at work upon the single upper hard limestone (Lockport) at the present cataract. The Genesee, on the other hand, is still in an early stage, because, although it has been at work just as long as Niagara has, and on the same rocks, the smaller amount of water determined a slower rate of cutting. Hence there are still three falls in existence in the Rochester Gorge, one about 100 feet high, over the Thorold quartzite (Fig. 676), a second 40 or 50 feet high, over the Clinton limestone (Fig. 677), and a third about 100 feet high, over the

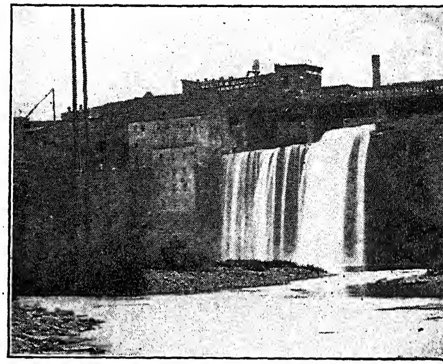


FIG. 678. — The upper falls of the Genesee River at Rochester — over the lower beds of the Lockport limestone. (Photo by the author.)

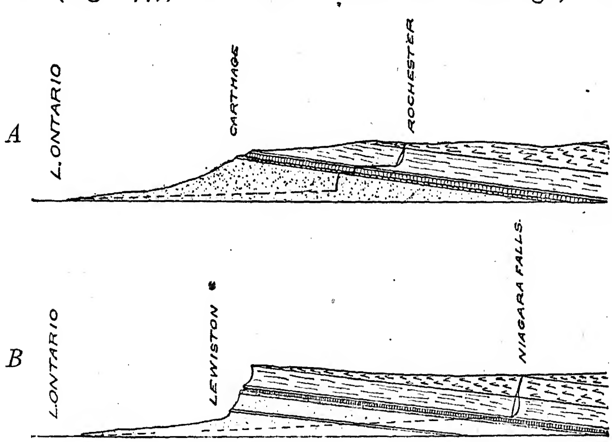


FIG. 679. — *A*.. Section of the lower Genesee River from Lake Ontario to Rochester, N. Y. *B*. Section of Niagara river from Lake Ontario to the Falls.

Lockport limestone (Fig. 678). In the Niagara gorge the lower two of these falls have long since disappeared, because the beds which produced them have passed below water-level on account

of the southward dip. The relative position of the waterfalls of the two rivers is shown in the diagram (Fig. 679).

The waterfall which began at the same time at Mt. Morris, cut more rapidly because it had chiefly soft shales and some sandstones to work upon. Hence, in the same period of time, it cut back not only across the plateau, where it formed a magnificent gorge 500 or more feet in depth and of a meandering character, but all the way back to Portageville, a distance of 18 miles, completely draining the Portageville lake. This cutting was not uniform, but wherever hard layers existed a separate fall came into being. To-day there are three of these, located at *A*, *B*, and *C*, respectively (Fig. 675), the upper one at *C* (Fig. 680) carrying the water down to the floor of the Oatka Valley, but the other two cutting below that because of the greater depth of the valley at Mt. Morris (Figs. 681, 684).

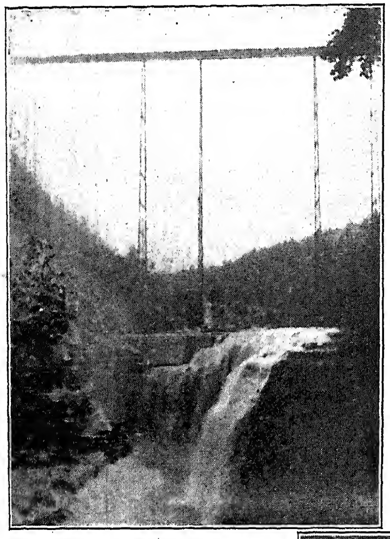


FIG. 680. — The Upper falls of the Genesee River at Portage. (Photo by author.)

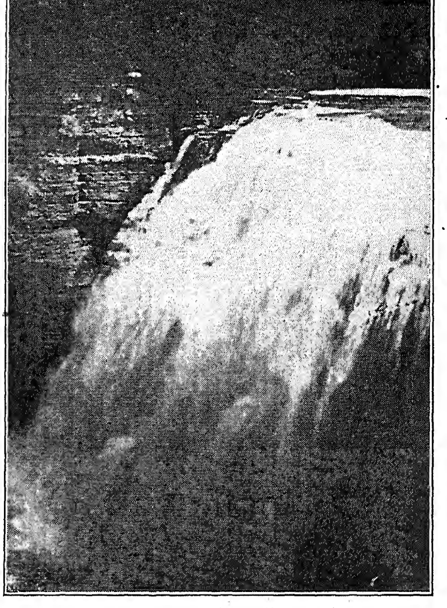


FIG. 681. — The middle falls of the Genesee River at Portage. (Photo by the author.)

Contrasting Features of the Modern Stream. — It is thus seen that the Genesee River is not

a normal stream, but one which has come into existence as the result of a complicated series of changes in the land surface, by reversal of the direction of drainage, and by the appropriation of parts of valleys of several older streams and the cutting of connecting gorges. Where the stream flows in the ancient valleys, the floors of which are always covered to a considerable depth with deposits made when these valleys were lakes, the stream itself has the aspect of maturity, winding across the flat bottom of a broad valley with sloping soil-covered sides (Fig. 682). Where, however, the stream has cut a connecting gorge, it is confined in a narrow chasm with steep rock walls. These are vertical wherever the current strikes the bank but form a talus-covered slope on the opposite side. A succession of such cliffs and slopes alternates on each side of the gorge. (See p. 416.)

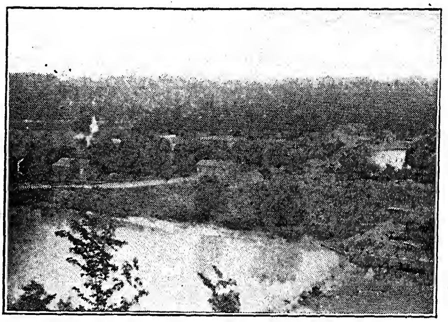


FIG. 682. — The open valley of the Genesee at Portageville above the upper falls. (Photo by the author.)

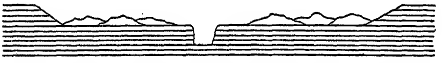


FIG. 683. — Cross-section of the old valley of the Genesee River, north of Portageville, N. Y., showing the mature broad valley, now partly drift obstructed, in the center of which the modern stream (reversed in flow) has cut a narrow gorge.

Where the stream has become incised below the level of the old valley-floor, a steep-sided narrow gorge occupies the center of a broad, open, shallow valley, as shown in the above diagram (Fig. 683).

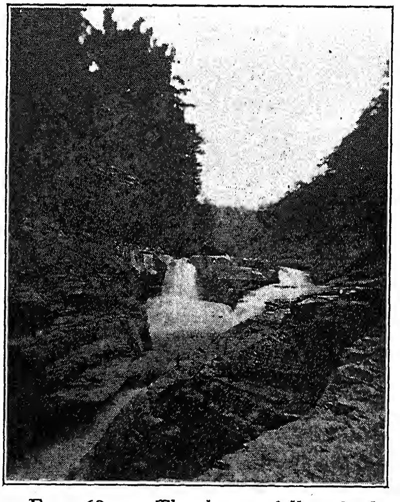


FIG. 684. — The lower falls of the Genesee River at Portage as it appeared in 1892. (Photo by the author.)

If the old valley was much encumbered by drift, some of this is also found in the gorge, whither it has been carried by landslides. Finally, where the stream is still actively cutting, a series of waterfalls (*A–C*) exist in narrow, steep-sided gorges, each waterfall being caused by a hard stratum of rock. Of the two portions flowing in mature valleys, the one above Portageville lies at a level which is about 500 feet above that of the mature portion below Mt. Morris. This difference of depth is taken up by the falls and rapids in the intervening gorge portions.

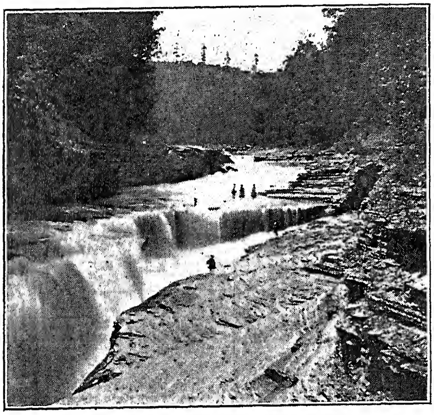


FIG. 685. — The lower falls of the Genesee at Portage in 1900.

In the lower of the three falls in the Portage gorge (Fig. 684) the phenomenon of the table rock or abandoned waterfall seen at Foster's Flats, Niagara, is repeated. Owing to a bend in the river, the current was deflected to the right side and cut there a deeper gorge (Fig. 685), leaving a triangular table rock, the site of the former fall, upon the left (Fig. 686). The following woodcut (Fig. 687), represents the conditions as they existed in 1840, while at present the falls in the narrower gorge have moved many hundred feet upstream. Owing to the jointing of this rock, the peculiar "Sugar Loaf" rock, shown in that illustration (and shown from below in Fig.

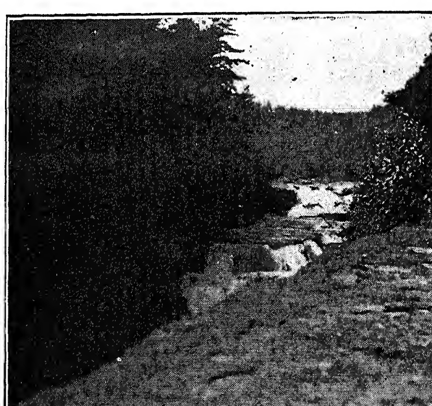


FIG. 686. — The table rock and narrow lateral gorge at the lower falls of the Genesee River, Portage, N. Y. 1892. (Photo by the author.)

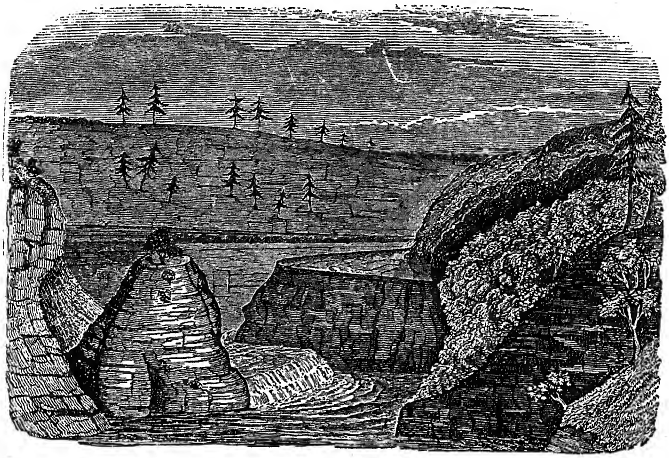


FIG. 687. — View of the lower falls of the Genesee at Portage as it appeared in 1840. (After Hall.)

688), was formed. The steps by which these features were developed are shown in the following series of diagrams (Fig. 689).

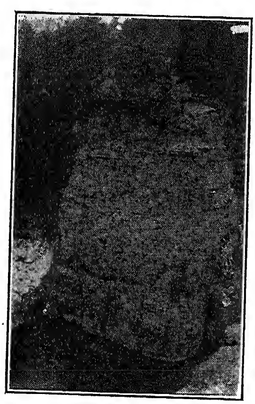


FIG. 688. — The "Sugar Loaf" rock seen from below (1892).

FIG. 689. — Diagram showing the development of the characters at the lower falls of the Genesee River at Portage. I–III, hypothetic; IV, conditions in 1840 (after Hall); V, conditions in 1892 (from a survey by the author).

The Grand Cañon of the Colorado River

General Characters of the Grand Cañon. — The Grand Cañon of the Colorado River is the most stupendous example of a river

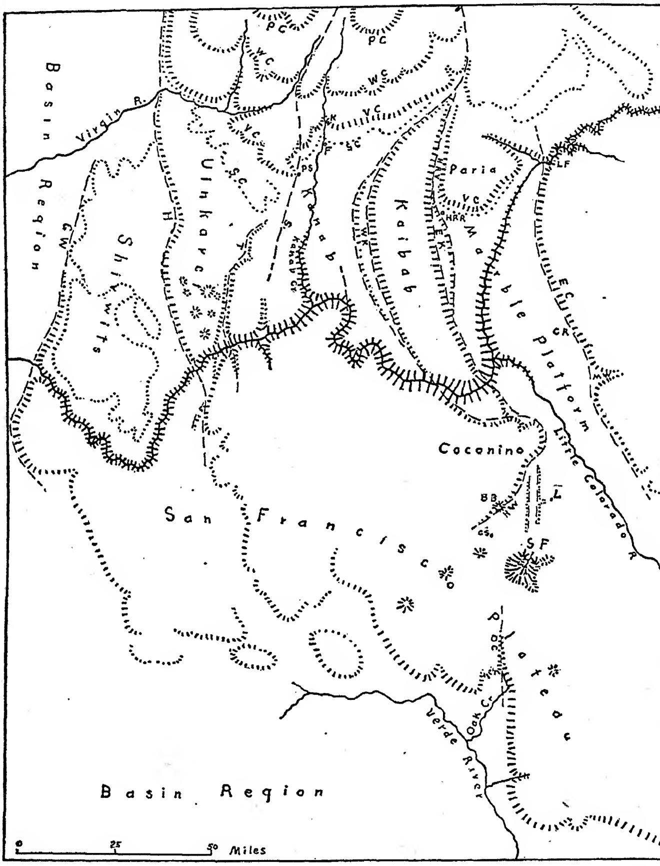


FIG. 690 *a*. — Sketch map of the Grand Cañon district, showing the succession of plateaus. (See fig. 690 *b*.) *EC*, Echo Cliff. *EK*, East Kaibab double monocline. *WK*, West Kaibab fault. *S*, Sevier fault; *T*, Toroweap fault, and scarp. *H*, Hurricane fault and ledge. *G W*, Grand Wash Cliffs and fault. (After Johnson.)

gorge to be found anywhere on earth. It is more than a mile in depth in its principal division, and its average width is eight miles, though some portions are wider. "Its sides are a succession of

rocky slopes and sinuous cliffs, some of which are huge steps with from 300 to 500 feet sheer descent" (Darton). The main section, the Grand Cañon proper, has a length of 125 miles, and it is divided into the *Kaibab* or eastern and the *Kanab* or western portions. The Kaibab is the deepest and most complex portion of the cañon, and in this the river has cut an inner gorge into the crystalline

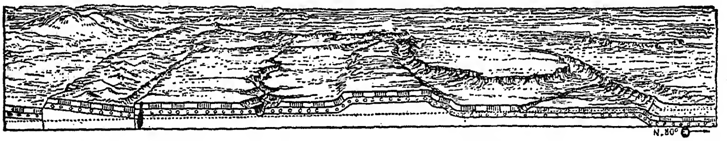


FIG. 690 *b.* — Block diagram and section of a part of the Colorado Plateau (after Powell). The section is drawn north of the Colorado and shows the principal formations. These are, at the base, the pre-Cambrian crystallines and ancient sediments (in white); the Tonto group of sandstones and shales (Cambrian) (in circles); the Carboniferous beds (limestones, shales, sandstones and limestones) (blocked); and the Permo-Triassic sandstones, etc. (fine dots).

On the right is Echo Cliff, an erosion ridge of Permo-Triassic sandstones in a monocline, the flexure of which is downward on the east. Along the section-line this forms a triangular ridge with a westward slope in conformity with the dip, almost as steep as the bold erosion scarp on the west. Next, west of this cliff lies the Marble Plateau formed by the nearly horizontal Carbonic (Kaibab) limestone and transected by the Marble Cañon. This was formerly also covered by the Permo-Triassic sandstone, a remnant of which forms the high Paria Plateau which rises above it in the background defined by the Vermilion Cliff. West of the Marble Plateau lies the Kaibab Plateau, which rises 2500 to 4000 feet higher and is formed of the same Carboniferous limestone (Kaibab). This plateau is bounded on the east by the East Kaibab monocline, which is generally a double flexure. On the west is the West Kaibab fault, here shown as a flexure. Southward this splits into three secondary faults with associated scarps, and they extend almost to the brink of the cañon. This fault lowers the formation and the surface to the Kanab Plateau still of the same limestone series. This is transected by the Kanab Cañon. In the distance is seen the Vermilion Cliff of Permo-Triassic sandstones and shales. The Kanab is separated from the Uinkaret Plateau by the Toroweap fault with downthrow on the west amounting to 600 or 700 feet near the Cañon. The Uinkaret is separated from the Shivwitz Plateau, still farther west, by the Hurricane fault ledge, with a recent displacement up to 1400 feet in addition to an older displacement. (See map on opposite page, Fig. 690 *a.*)

basement-rocks. In the Kanab portion, which is much less diversified and picturesque, the inner gorge is cut into the lower member of the late Palæozoic series (the Red Wall limestone), the surface of which forms a broad platform about two miles wide on either side and a thousand feet below the summit of the plateau, which stands nearly 7000 feet above sea-level. Above the Kaibab portion of the Grand Cañon the river has cut the Marble Cañon, which is

65 miles in length and extends nearly north and south, being joined nearer its lower end by the cañon of the Little Colorado. (See map, Fig. 690 *a*, and the more detailed map, Fig. 691.) The Marble Cañon is cut through the Carbono-Mississippian limestones, shales, and sandstones down to and into the Cambrian (Tonto beds), but to the west of it a broader open valley exposes the older pre-Cambrian rocks, here raised to greater altitude. The reason for these differences in the rock sections will become apparent when the general structure of the country is understood.

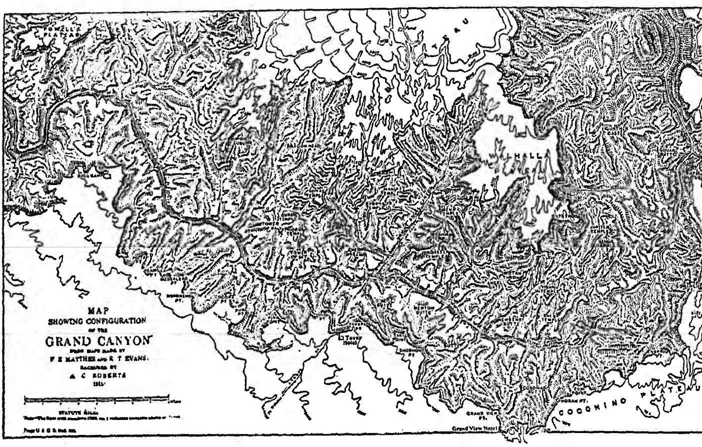


FIG. 691. — Map of the Grand Cañon and part of the Marble Cañon on the right. (U. S. G. S.)

Rocks Exposed in the Grand Cañon. — In the immediate vicinity of the cañon the strata which compose the plateaus are of Palæozoic and older age. At the base of the series lie the granite and other crystalline basement rocks, these being exposed in the bottom of the cañon from about the Grand View Point westward for 35 miles or more (map, Fig. 691). The river has cut an inner gorge in this resistant rock, to a depth of 800 to 1000 feet, as is shown in the photograph taken from El Tovar and reproduced in Fig. 693, and in the cross-section of the cañon from the same point (Fig. 694). These rocks, which form dark rugged ledges in the inner gorge, terminate upwards in a very level surface of erosion (a peneplane) and upon them, over wide areas, rest the horizontal Tonto sandstones, about 150 feet thick, followed by the Tonto shales of greenish color and about 800 feet in thickness. These formations belong to the Cambrian series of rocks. The surface of the Tonto sandstone forms a plateau or terrace on either side of the inner gorge, averaging a mile in width, while the shales which overlie it form long slopes interrupted by subordinate limestone and sandstone ledges. The platform and inner gorge are char-

acteristic features and are well shown in the topographic map of the cañon (Fig. 691) and in the photograph (Fig. 693).

In the broad part of the cañon which lies northeast of Grand View (west of the Marble Cañon) and in some other sections (Shinumo basin, parts of Bright Angel cañon, etc.) another series of old rocks appears between the Tonto sandstone and the basal granites and other crystallines. This pre-Cambrian series is known as the *Grand Cañon Series*, and is divisible into two parts. The lower division (*Unkar group*) consists of basal conglomerates, limestones in thick dark beds, bright red shales and upper heavy quartzites and brown sandstones. The higher division (*Chuar group*) is seen only in the region west and northwest of the mouth of the Little Colorado, and consists of sandstones, shales, and limestones. The

Fig. 692. — General view of the Grand Cañon.

beds of the Grand Cañon series, which have a total aggregate thickness of 12,000 feet, dip rather steeply to the north and northeast, and are in marked contrast with the nearly horizontal Tonto beds which overlie them unconformably. The relation is shown in the section (Fig. 694). The surface of the inclined Grand Cañon beds was beveled across by erosion and worn into an undulating plain before the Tonto beds were deposited upon it.

Next above the Tonto shales, and like these nearly horizontal, is a massive hard compact limestone about 500 feet thick and of pale-blue gray color when freshly broken. It forms great cliffs the faces of which are stained red from the wash of the red beds which overlie it, and on this account the rock has been named the *Red-wall limestone*. Its cliffs form prominent features in the scenery of the cañon, and they are well indicated by the heavy shading above the Tonto platform in the map (Fig. 691)

(see also the section Fig. 694). In the photograph (Fig. 693) the prominent dark cliff above the middle of the view is formed by this limestone. This limestone also forms the caps of many flat-topped spurs and buttresses, and of outlying buttes and towers such as Cheops Temple, Newberry Butte, Sheba Temple, Solomon's Temple, and many others.

Next above the Red-wall limestone lies a series of red shales interbedded with thick layers of red and red-brown sandstone, the whole forming the

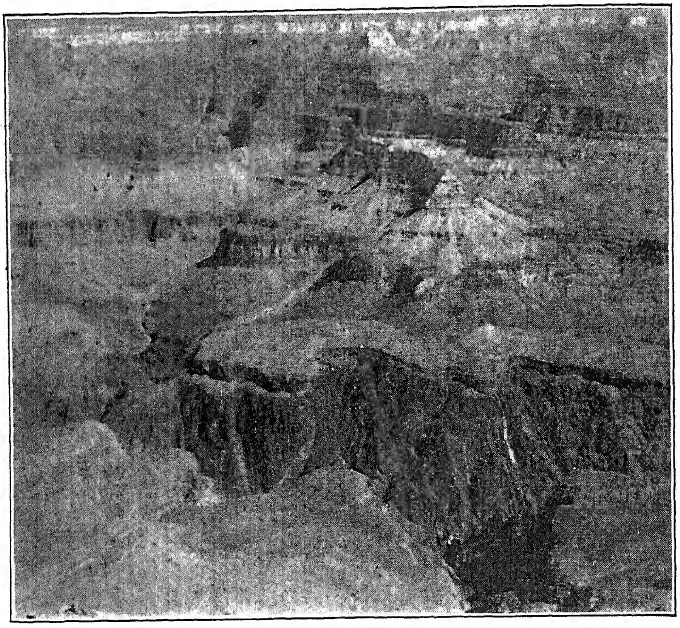


Fig. 693. — Telescopic view of the Grand Cañon of the Colorado, from El Tovar Hotel, showing the crystalline rocks (granite and gneiss) at the base unconformably overlain by the horizontal Palæozoic strata. Resting directly upon the granite, the Tonto sandstone forms a platform in the foreground; the first cliff beyond the gorge is formed by Unkar quartzites covered by Tonto shale. The prominent cliff three fourths the way up is the Red-wall limestone, and it is covered by the Supai Red Beds. The Red-wall limestone forms the prominent butte, Cheops Pyramid, near the center of the picture, while the higher butte is Buddha Temple, a detached part of the Kaibab Plateau which forms the background. A section across this part of the cañon is given in Fig. 694.

Supai formation, which has a total thickness of 1100 feet. Because of their hardness, the sandstones cause a succession of steps in the middle of the slope formed by the red shales. These red beds constitute a large part of many fine promontories and ridges which project far out into the cañon. Many of the buttes and towers are also formed of them. The next higher division is the heavy *Coconino sandstone*, 300 feet thick, and

this forms a vertical gray cliff in the cañon wall, 800 feet below the top. It is massive and strongly cross-bedded. On top of it lies the *Kaibab limestone*, a slabby light gray limestone nearly 800 feet thick, which everywhere causes the terminal cliff and the summit of which forms great forest-covered plateaus. This is the highest rock exposed in the cañon walls, and it and the underlying formations to the top of the Tonto group belong to the "Carboniferous" series of rocks. Between them and the underlying Tonto group is a great break in succession, *i.e.*, a hiatus, which leaves the great middle portion of the Palæozoic series unrepresented.

This rock series was once covered by higher beds, but these have all been eroded from the immediate vicinity of the cañon. They comprise vari-colored shales and red sandstones of Permian and Triassic age, portions of which are now seen in the Vermilion Cliffs and in Echo Cliff (see Fig. 690 *a* and the stereogram, Fig. 690 *b*). A still higher series of white sandstones (Jurassic) is seen in the White Cliffs, which form the edges of more elevated plateaus, far to the north of the cañon.

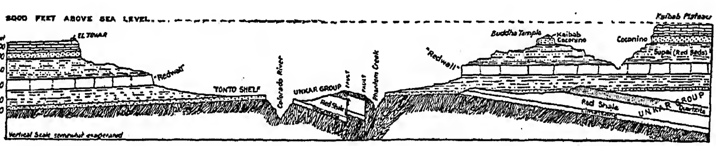


FIG. 694. — Section across the Grand Cañon west of Bright Angel Creek. From El Tovar to Kaibab Plateau, showing the unconformity between the basal crystallines and the Unkar Group, and that between the latter and the Tonto formation of the Palæozoic. (U. S. G. S.) *A*, Kaibab-limestone; *B*, Coconino sandstone; *C*, Supai (Red Sandstones and shales); *D*, Red-wall limestone; *E*, Tonto shales and Sandstones (at base); *F*, Granite, etc.

General Character and Development of the Region. — Taking a broad view of the country into which the Grand Cañon is cut, we recognize that it consists of a series of great plateaus composed of nearly horizontal strata. These plateaus, known collectively as the Colorado Plateaus, are separated from one another by monoclinal flexures or by cliffs located along lines of faulting. The general trend of the axes of the flexures, and that of the fault lines, is north and south, or approximately at right angles to the Grand Cañon. (See map, Fig. 690 *a*, and diagram, Fig. 690 *b*.) Originally the deformation was entirely by monoclinal flexures which ascended westward, so that the region was composed of a series of huge steps rising westward, each separated from the others by flexures, and elevated from one to several thousand feet above the one next below. During or shortly after the flexing, the monoclines of the western half of the series broke and the elevated blocks settled

down again, the depression in general being progressively more pronounced westward, so that a descending series of steps was produced. Thus originated the peculiar type of faulting of this region previously referred to (p. 600), in which the up-flexed portion became the downthrow block, the strata of which bend down near the fault-plane, while the strata of the upthrow block bend up near that plane, this being the reverse of the bending produced by drag in ordinary faulting. (See Fig. 518 *b*, p. 602.) In the eastern half of the region, the original monoclinal flexures remained unbroken so that the steps descended both eastward and westward from the high or central area: eastward by a succession of monoclinal flexures; westward by a succession of faults.

This period of disturbance was followed by extensive erosion, during which the country was reduced to a peneplane, both the fault and the flexure-steps being obliterated. It was into this peneplaned country, the surface of which was now formed of different rocks in the various blocks, that the westward-flowing Colorado began to cut its cañon. Over parts of this peneplaned surface basaltic lavas were poured out, covering adjoining portions of contiguous fault-blocks, in which the surface was often cut on different formations. A second period of faulting, in the same direction, ensued, but this affected chiefly the western faults (Grand Wash and Hurricane). Where these were crossed by basalt flows, the part resting upon the western block was lowered, relatively, with that block, during the faulting. In the ensuing second cycle of erosion, the softer strata were stripped from off the various blocks, except where protected by the basalt layers, and thus the step-like topography was reproduced, but this time the surfaces of the several plateaus in the vicinity of the cañon were formed by the Kaibab limestone, the resistant upper member of the Carbonic series. Portions of the higher formations, however, remained to form the more elevated plateaus north of the cañon, as seen in the stereogram (Fig. 690 *b*) and in the map (Fig. 690 *a*). The principal westward-facing scarps of the region thus represent *resequent* fault-scarps, though parts of the Hurricane and the Grand Wash cliffs are new fault-scarps, produced by a third period of faulting, after the cutting of the Grand Cañon had progressed to a considerable extent.

As the Colorado had learned to flow westward upon the old peneplaned surface, formed during the first cycle of erosion, it continued

in this direction upon the renewed great uplift of the country. This latest period of erosion witnessed the cutting of the great cañon, which, though of such magnitude, is only the latest erosion feature in a region which has undergone a succession of uplifts and down cutting of vastly more stupendous proportions and all within the space of time which has elapsed since the close of the early Tertiary period. Because of the differential elevation of the several blocks into which the cañon is cut, the bottom of the cañon in the several sections is formed by different members of the rock succession.

Fig. 694 *a*. — Major John Wesley Powell.

The characters of the Grand Cañon were practically unknown to the world, until a heroic exploring party traversed it from end to end in 1869, under the leadership of that intrepid geologist, Major John Wesley Powell (portrait, Fig. 694 *a*), one of the organizers and early directors of the United States Geological Survey. Since that day it has become a favorite region for study and inspirational contemplation, having in recent times been made readily accessible to the general tourist. To the student of geology it serves as the most wonderful object lesson in cañon cutting which our country affords.

Land Forms Due to Glacial Sculpture

Glaciers are very important agents in the sculpturing of the landscape, their mode of cutting being that already set forth in an earlier chapter (pp. 433–435). We shall here summarize only the characteristics of the main types of land-forms due to glacial sculpturing.

The Cirque, Arête, and Horn. — One of the most characteristic erosion features of glaciated mountain districts is the *cirque* or glacial amphitheater at the head of the glacier (Fig. 303, p. 366; Figs. 695 *a*, *b*). Where glaciers have entirely disappeared, these steep-walled semicircular indentations remain as eloquent witnesses

of former glacial occupancy, for no agent but the glacier is known to be capable of producing such a feature. Where several cirques occur side by side, they may be separated by narrow ridges, which, with the growth of the cirque by continued cutting, will become sharper and sharper, with knife-edge crests, and this eventually results in the production of a strongly serrated ridge or *arête* (Fig. 696 *a*).

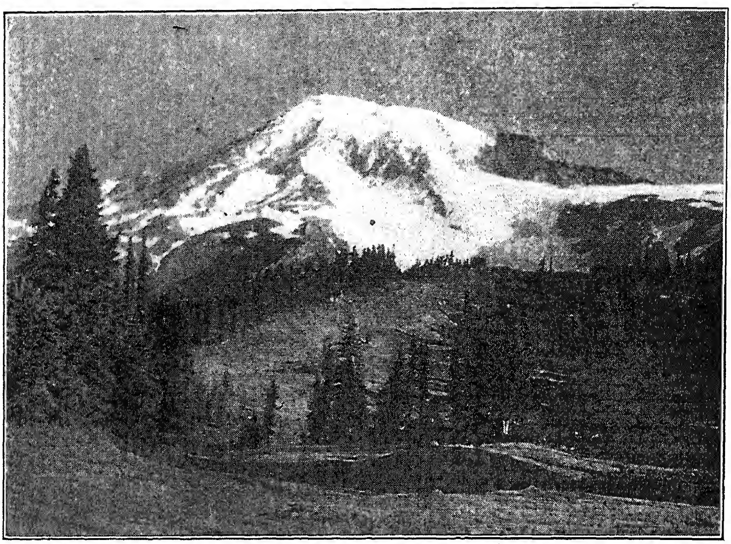


FIG. 695 *a*. — South slope of Mt. Rainier, with Paradise Park in the foreground. Note the glacial cirques which are being cut back into this maturely dissected volcano. (Photo by A. H. Barnes, courtesy of D. W. Johnson.)

As we have seen in an earlier chapter, the cirque is produced by the plucking action of the lower portion of the glacier mass which occupies the valley in the mountain side. The *bergschrund* or crevasse at the head of the glacier formed by its forward movement permits the thawing and refreezing of the ice at the bottom, and this brings about a loosening of rock masses from the base of the cirque. Its walls, which originally were those of a sloping valley become more and more steepened. The floor of the cirque also may be deepened into one or more basins by the scouring action of the moving ice, and such basins may remain filled with water after the ice has melted away entirely, forming rock basin lakes or tarns. Lakes may also be held in an ice-abandoned cirque by morainal matter deposited across its mouth (Fig. 696 *b*).

Where cirques have been cut into an old table-land from various directions, the region after the disappearance of the ice presents a remarkably scalloped character which has been aptly compared with a heavy piece of dough from which biscuits have been cut, the hollows left by the biscuit cutter representing the cirques, and the remnant of the dough, the irregular ridges of upland remaining.

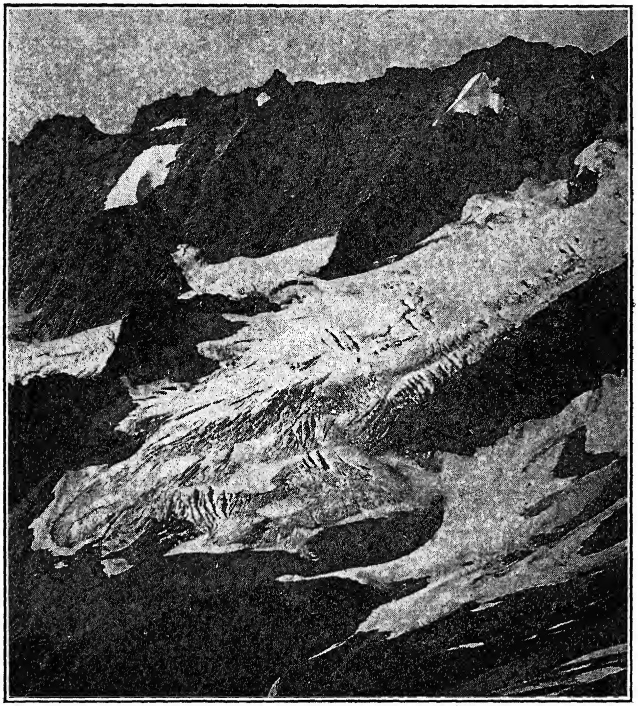


Fig. 695 *b*. — Glacier at Cascade Pass, — Glacier Peak quadrangle, Washington; showing steep walls of cirques separated by narrow arêtes; marginal crevasses on the ice and abundant morainal material are shown in the foreground. (Photo by B. Willis, for U. S. G. S., courtesy of *Popular Science Monthly*.)

At first, the cirque is scarcely wider than the valley below in which the glacier lies, but by continual sapping it becomes enlarged in all directions, so that its form, with reference to that of the valley extending from it, has been aptly compared to that of the large rounded head of a nail. Further growth of the cirques may produce compound or scalloped forms with subordinate cirques around the margin of the principal one. In this manner a complex

"grooved" upland is produced, which later, by the sharpening and partial destruction of the dividing ridges, produces a sharply

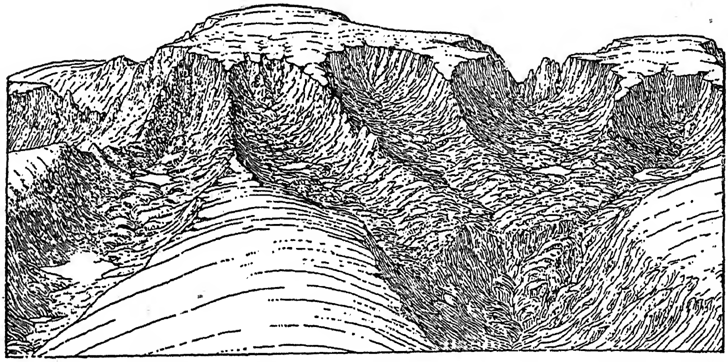


FIG. 696 *a*. — Diagram of a mountain region from which the former glaciers have melted away, leaving the cirques to testify to their former presence. Some of the cirques diverge, leaving a broad rounded ridge between them, others converge, being separated only by a serrated knife-edge or arête (grat). (After Davis.)

"fretted" upland surface, such as is characteristic of the summit of Mont Blanc and other regions of the Alps. Sharp-toothed comb-like ridges, called *arêtes* or *grats*, dividing the cirques, are

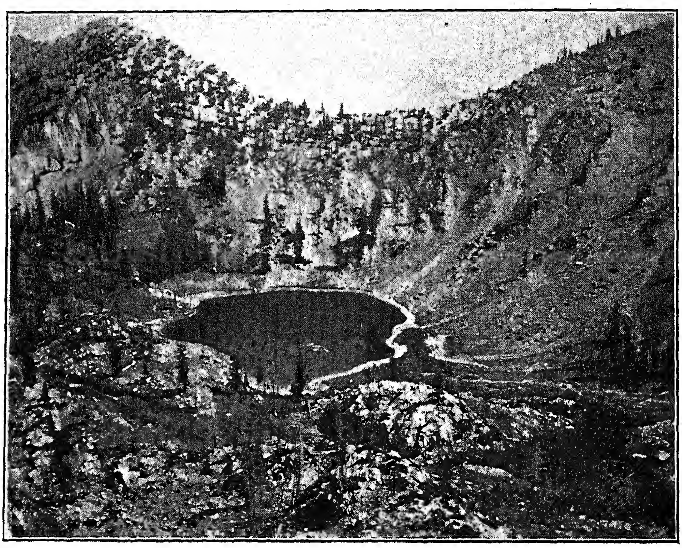


FIG. 696 *b*. — A glacial lake or tarn in an old cirque. Utah. (Photo by F. J. Pack.)

characteristic of this stage, and at the junction points of such comb-ridges sharp pyramidal peaks or "horns" arise as the erosion remnants of the highest portion of the original mountain mass. Of these, the Matterhorn (Fig. 697), the Aletschhorn, and many others are typical Alpine examples. Mount Sir Donald in the Selkirk Mountains of Canada is a typical American example.

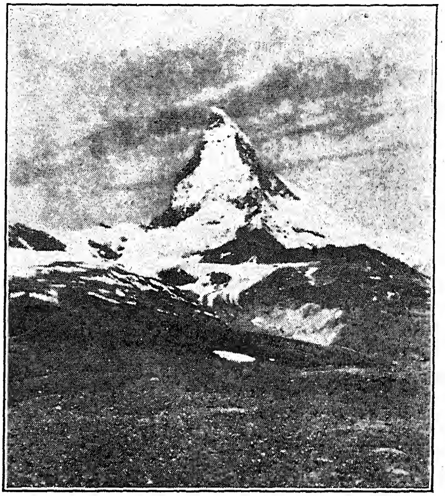


FIG. 697. — The Matterhorn, a typical Alpine peak or "horn" in Switzerland, as seen from the Gornergrat. (Photo by D. W. Johnson.)

The U-shaped Valley. — The normal section of a young river valley is more or less V-shaped, the greatest cutting taking place at the bottom and downward, while weathering pushes

FIG. 698. — The Yosemite Valley, a typical U-shaped young glaciated valley, much over-deepened so that the side streams now flow in Hanging Valleys and enter the main valley by Waterfalls.

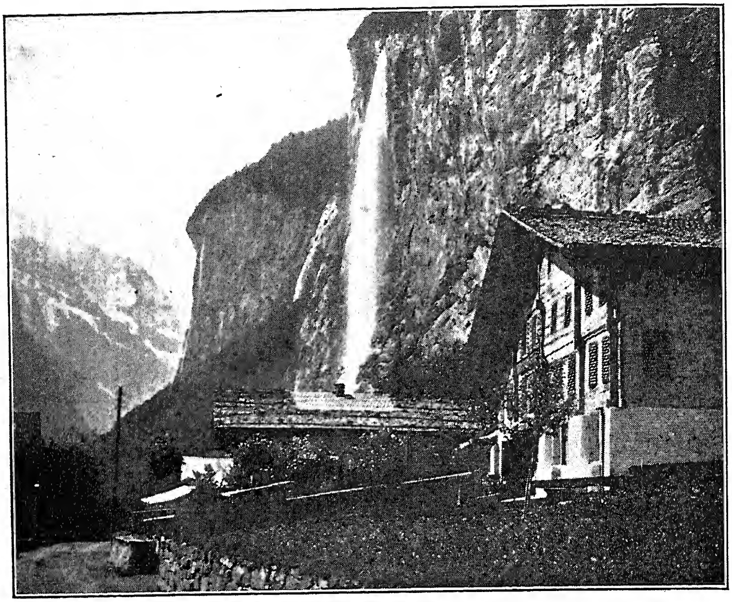


FIG. 699. — The Lauterbrunnen Valley; a young glacial trough, similar to the Yosemite Valley. It is especially noted for the splendid cataracts which enter it from hanging valleys. (Courtesy D. W. Johnson.) (See Fig. 310, p. 372.)

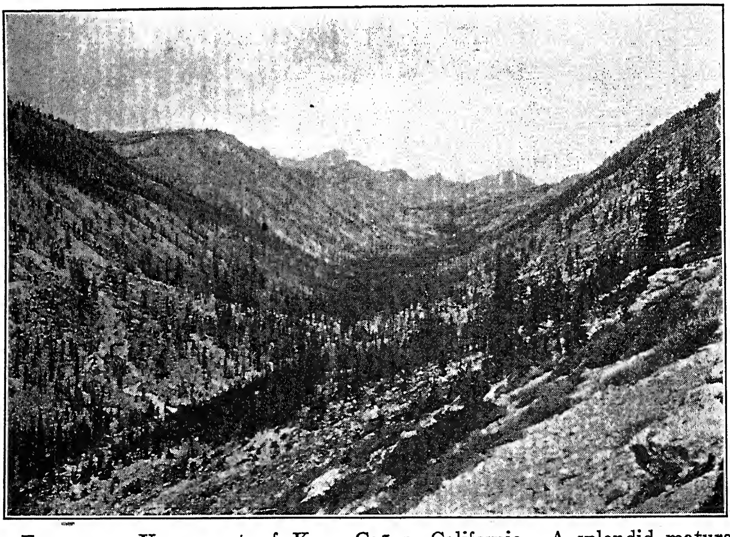


FIG. 700. — Upper part of Kern Cañon, California. A splendid mature glacial trough showing the typical catenary curve. (Photo by Gilbert, U. S. G. S. Courtesy D. W. Johnson.)

back the sides of the valley most rapidly in the upper portion. With increasing age the floor of the valley is widened to a flat surface, but the sides retain their slopes. When such valleys are occupied by moving glaciers, cutting takes place not only at the bottom, but on the sides as well, and the section of the valley changes to a U-form, with precipitous cliffs often of great height. This constitutes the stage of youthful deepening of river valleys by ice and presents the most picturesque aspect of such erosion. It is well shown in the great Yosemite Valley of California (Fig. 698), which has been scoured out by ice to a depth of more than two thousand feet, and in the beautiful Lauterbrunnen Valley of Switzerland (Fig. 699), which has a very similar character. (See also Fig. 310, p. 372.) Where a valley has long been occupied by a large ice stream, the walls of the resulting trough are smooth and somewhat flaring, and the bottom beautifully rounded (Figs. 700, 701). It no longer has the parallel sides of a U-shaped valley and is better called a glacial trough. Most glaciated valleys belong to this category.

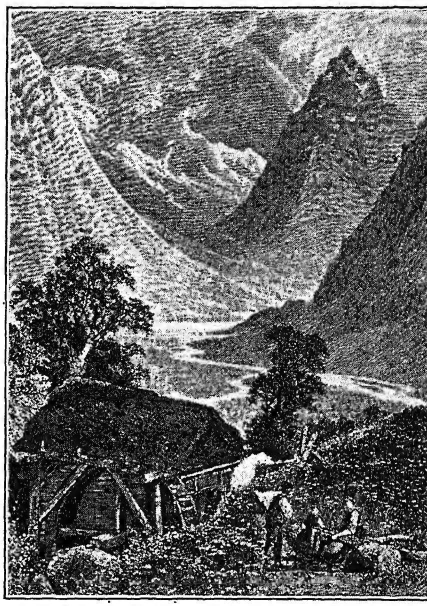


FIG. 701. — Catenary curves of glacial trough in Norway. View from Moldestadt. (Courtesy D. W. Johnson.)

If the original river valley is an irregular one, with rocky spurs projecting from alternate sides, these spurs will gradually be worn off by the ice, and their truncated faces will form a characteristic feature of such a valley that has been glaciated. Hence the steepened sides and the truncated spurs form characteristic topographic features by which young glaciated valleys may be recognized, while the flaring sides and general smoothness of form indicate a valley long occupied by ice (Fig. 702 *a*, *b*).

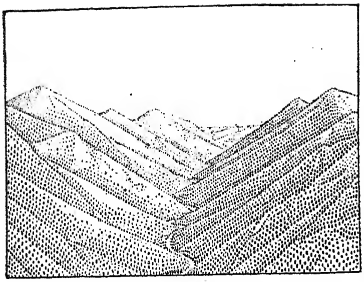


FIG. 702 *a.* — River valley with numerous spurs and a V-shaped form. (U. S. G. S.)

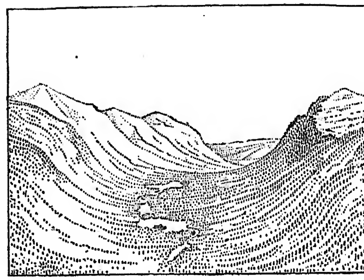


FIG. 702 *b.* — The same valley as that shown in Fig. 702 *a* after glaciation. The spurs have been truncated and the valley is broadly U-shaped. (U. S. G. S.)

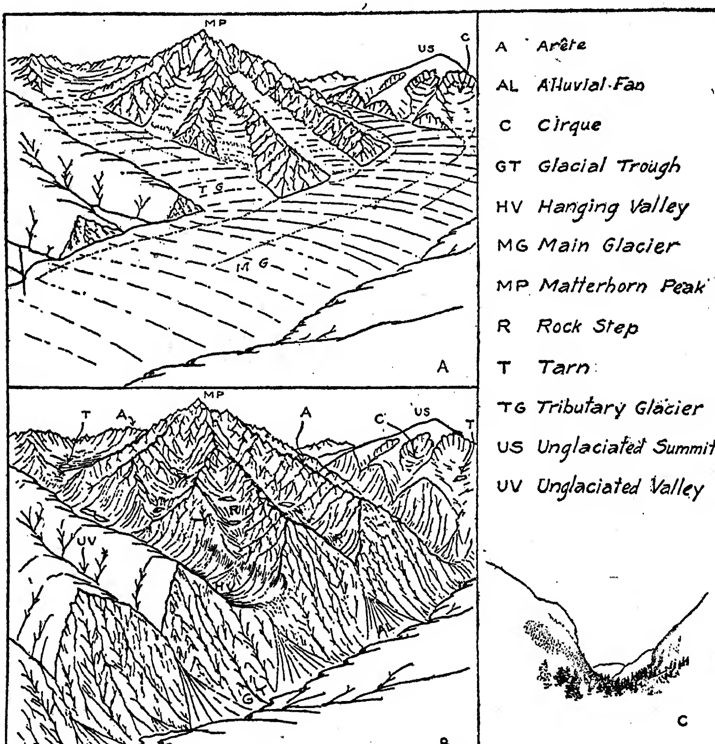


FIG. 703. — Land forms due to ice sculpture. *A.* A mountain mass occupied by a glacier system. The surfaces of the main and tributary valleys are in accord. *B.* The same mountain mass after melting of the glaciers. The floor of the main valley lies far below that of the tributary valleys, which now form hanging valleys upon its side. (After Davis.) *C.* Sketch of a glaciated valley showing the U-shaped form. (*Military Geology.*)

Overdeepening; Hanging Valleys. — A normal river valley will, in general, be joined by its tributary valleys at grade, that is, the floors of the two valleys will be essentially in accordance at the point of junction. In glacially eroded valleys, however, this

FIG. 704. — Diagrams illustrating the transformation of a lateral stream valley into a hanging valley by glacial erosion of the main valley: *A*, by widening of the main valley without deepening; and *B*, by over-deepening of the same without essential widening.

is frequently not the case, for the main valley which is occupied by the larger glacier may be greatly deepened by it, while the lateral one, occupied by smaller glaciers or by none, may be deepened slightly or not at all. Tributary glaciers have their surfaces

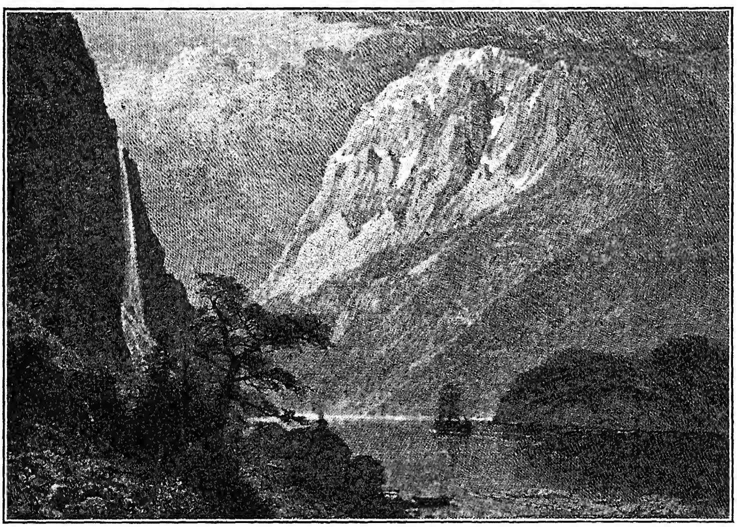


FIG. 705. — The Norwegian fjords are partially submerged glacial troughs into which side streams fall in cataracts from hanging valleys. The Naero Fjord, from Gudvangen. (Courtesy D. W. Johnson.)

in accord with the surface of the main glacier at the point of junction, but their floors may be at very different levels (Fig. 703). This might be due to the widening of the main valley at the bottom (*A*) (Fig. 704), but is more commonly produced by overdeepening (*B*) or by both. When the ice finally melts away from the

valleys, the point of junction of the lateral with the main valley is found to be high up on the side of the main valley, the lateral valley then being spoken of as a hanging valley. Such hanging valleys are very characteristic of glaciated districts, as is so well shown in the falls of the Yosemite and Lauterbrunnen valleys, which drop from hanging valleys high up on the side of the main trough (Figs. 698, 699), and in many of the beautiful falls of the Norwegian fjords (Fig. 705). Hanging valleys may also be produced in other ways. Thus, where a waterfall in the main valley cuts beyond the mouth of the small tributary valley which formerly joined it at grade above the waterfall, this valley will, for a time after the recession of such a waterfall, remain as a hanging valley on the sides of the main gorge. The valley of the Bloody Run on the side of the Niagara Gorge is such a hanging valley, and there are many examples of this type in the gorges of young streams, as for example in the Genesee (Fig. 706). In broad, open valleys, however, such a relationship generally points to glacial overdeepening of the main valley.

FIG. 706. — Falls of a hanging valley on the side of the Genesee Gorge at Portage, N. Y. The difference in elevation between the floors of the two valleys is about 200 feet, and is due to the recession of the cataracts of the main valley. (Photo by author.)

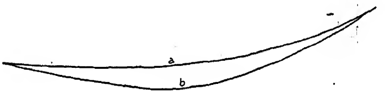


FIG. 707. — Longitudinal profile of a river valley (*a*); and of the same valley after it has been deepened by a glacier (*b*). Note that the valley in the second case is deeper above the mouth, so that it would hold a lake after the melting of the glacier.

Glacial Lakes, Tarns, and Fjords. — Glaciers do not deepen their channels in a uniform manner any more than rivers do. Near the head of the glacier, as well as near its front, the deepening is, as a rule, to a

lesser degree than between these two points. In consequence, the profile of a glacial trough will be more strongly concave than that of a normal river valley (Fig. 707). When such a valley is uncovered by the melting of the ice, a rock tarn or lake will remain behind in the deepened part. This lake may attain additional depth by the building of a morainic dam across the mouth of the valley. Many of the beautiful Scottish lochs are examples of such lake basins of glacial origin, and a similar origin is ascribable to the Finger Lakes of New York state.

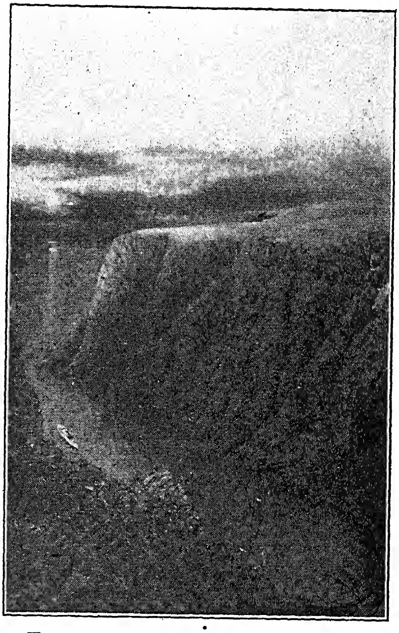


Fig. 708. — A typical Norwegian fjord, showing U-shaped glacial trough and the relatively flat upland of the Norwegian peneplane. (From D. W. Johnson's *Shore Processes*, etc. John Wiley and Sons.)

When the deepening by ice has proceeded to a level below that of the sea, or if an over-deepened valley near the coast is carried down by a subsidence of the land, the sea will occupy a part of such a valley, and a *fjord* is produced. Such fjords are very characteristic of the bold coast of Norway (Figs. 705, 708), and they are found in Scotland and elsewhere as well. The Hudson River (Fig. 709) has the character of a fjord, the depth being over 600 feet from water level to rock bottom in the Highlands, whereas opposite New York City, it is only somewhat over 300 feet. That this is not due to differential subsidence or downward bowing of the land is shown by the regular rise of the crest-line of the gorge (the surface of the old peneplane), for any unequal subsidence affecting the river bottom would also affect this crest-line. The relationship is shown in the diagram on page 804 (Fig. 710).

There are many drowned river valleys along the Maine coast, but it is not known whether these have the characteristics of true fjords, that is, whether they are deepened by glacial erosion, less at

the mouth than some distance back of it (Fig. 711). A map of a typical fjorded coast, that of New Zealand, is shown in Fig. 712.

The Tinds and Nunataks. — Around the margins of ice caps which cover elevated tracts of country, a special form of erosion takes place. Where the ice spills through notches in the rock

FIG. 709. — The gorge of the Hudson in the Highlands. North of West Point.

margin, active erosion goes on at those points, and the result is often the production of a conical rock hill by the reduction of a mass of rock enclosed by the spill-overs of such an ice cap. So long as such a mass is enclosed by ice, above which it projects, it is called a *nunatak*, as are all rock-masses projecting above the

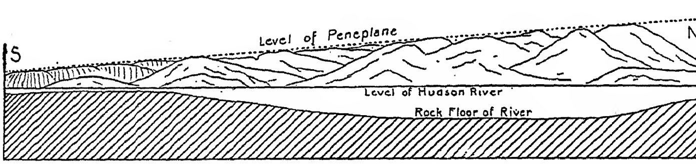


FIG. 710. — Profile of the Hudson River from New York City through the Highlands, showing the fjord-like excavation above the mouth and the gradual northward rise of the peneplane.

marginal portion of the ice-field. When freed by the melting of the ice, such a conical hill due to glacial erosion is called a *tind*. Unlike the conical hills or *horns* produced at the head of the mountain glaciers by sapping, the tind is produced at the lower end of the glaciers by lateral erosion. Such tinds are frequently met with in higher latitudes where ice-caps are still in existence.

Erosive Work of Valley and Mountain Glaciers Contrasted with That of Ice-Caps and Continental Ice-Sheets

Valley and mountain glaciers tend to accentuate the relief of the country, especially in their middle and upper courses. Ice-caps and continental glaciers, on the other hand, tend to plane down the relief of the country which they cover and produce an accentuation of the topography only at their margins.

The Sculpturing of the Edge of the Land

The edge of the land, that is, the sea-coast and the coasts of large lakes, are subjected to a sculpturing process by the waves and

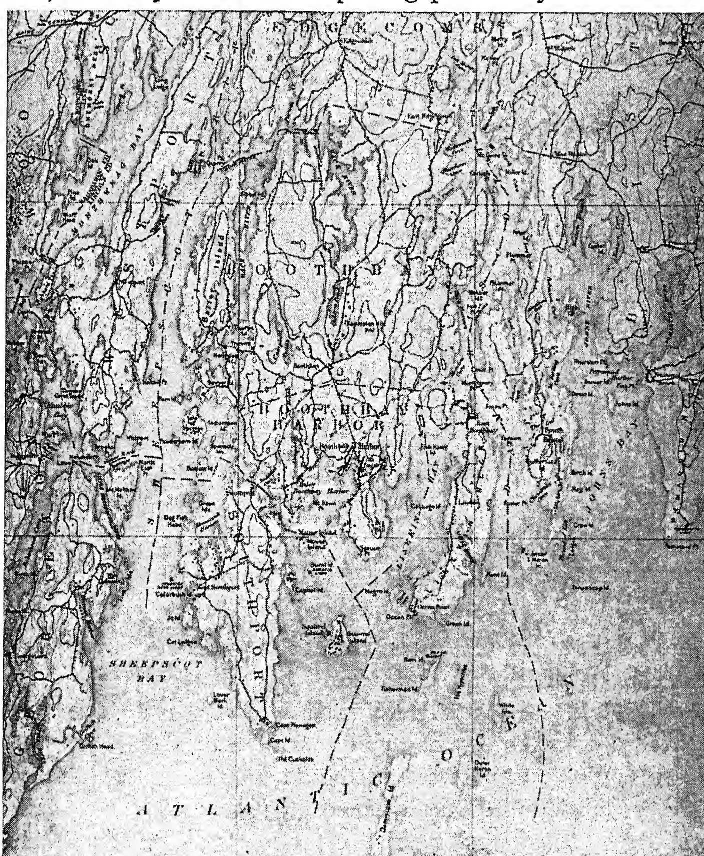


Fig. 711. — Map of a section of the coast of Maine, showing the topography produced by drowning of river valleys.

currents, with the production of special erosion forms, the more important of which we may consider.

Young and Mature Coasts. — A young coast-line is one but recently established by the relative change in the level of land and sea. Such a coast-line is a regular one if it is formed upon a young surface of a recently emerged sea or lake-bottom, for in such a case the coast marks merely the intersection of two planes, that

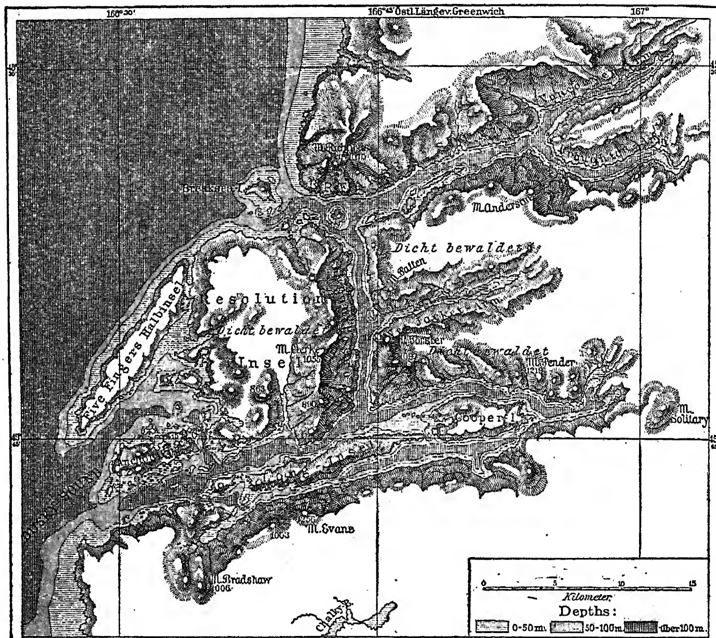


FIG. 712. — Fjord coast of Dusky Sound, New Zealand. A young coast-line upon a strongly dissected land surface. (British Admiralty Chart, from Ratzel, *Die Erde.*)

of the sea and that of the young coastal plain. A young coast-line upon an old land surface, *i.e.*, a peneplane, will also be on the whole fairly regular, though such regularity will be less pronounced than in the case of a young land. But a young coast-line formed upon a maturely dissected land surface will be one of extreme irregularity, such as is shown, for example, on the Maine coast of New England (Fig. 711), or the coasts of Norway, Sweden, and elsewhere (Fig. 712). A mature coast-line on any land surface tends toward regularity of outline, for the projecting headlands will

be cut back and the reëntrants will be bridged by the formation of bars and beaches.

Erosion on the Coast of a Young Land. — A newly emerged coastal plain of gently seaward-dipping strata will not immediately be effectively attacked by the waves, because the water near the shore is as a rule too shallow for vigorous wave erosion. In such a case, an off-shore bar will be built first, at the line where the shoaling determines the breaking of the prevailing storm waves for that

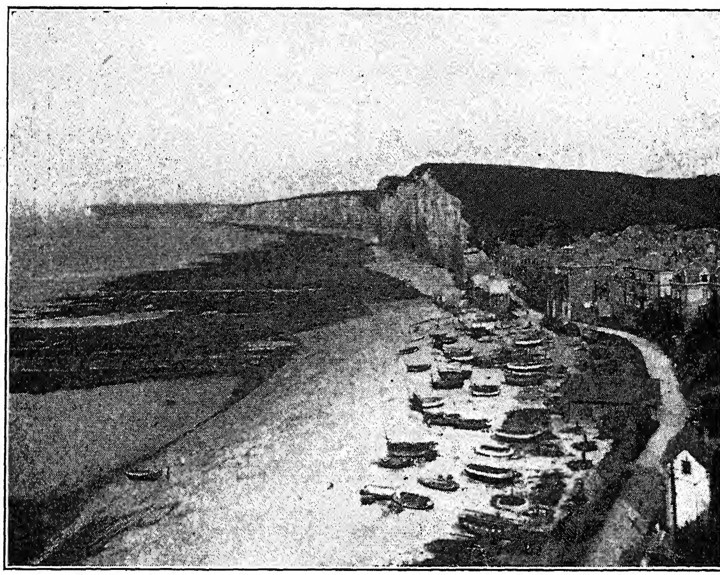


FIG. 713. — Wave-cut chalk cliffs near Fécamp, France. (From D. W. Johnson, *Shore Processes*, John Wiley and Son.) Note the marine bench in front of the cliffs, only partially covered by the lighter beach sand.

coast. This bar is built by the eroding of the bottom by the breaking wave, the hurling forward of the material removed, and its deposition in shallower waters, from which it eventually emerges as an off-shore bar, as already described (p. 330, p. 539). In front of the bar the water has been sufficiently deepened for wave attack, behind the bar a shoaling of the lagoon takes place, with the formation of peat deposits, and eventually, perhaps, a strip of dry new-made coastal land.

Meanwhile the waves continue to attack the bar, cutting it away, while the sand dunes travel inland over the lagoon deposits.

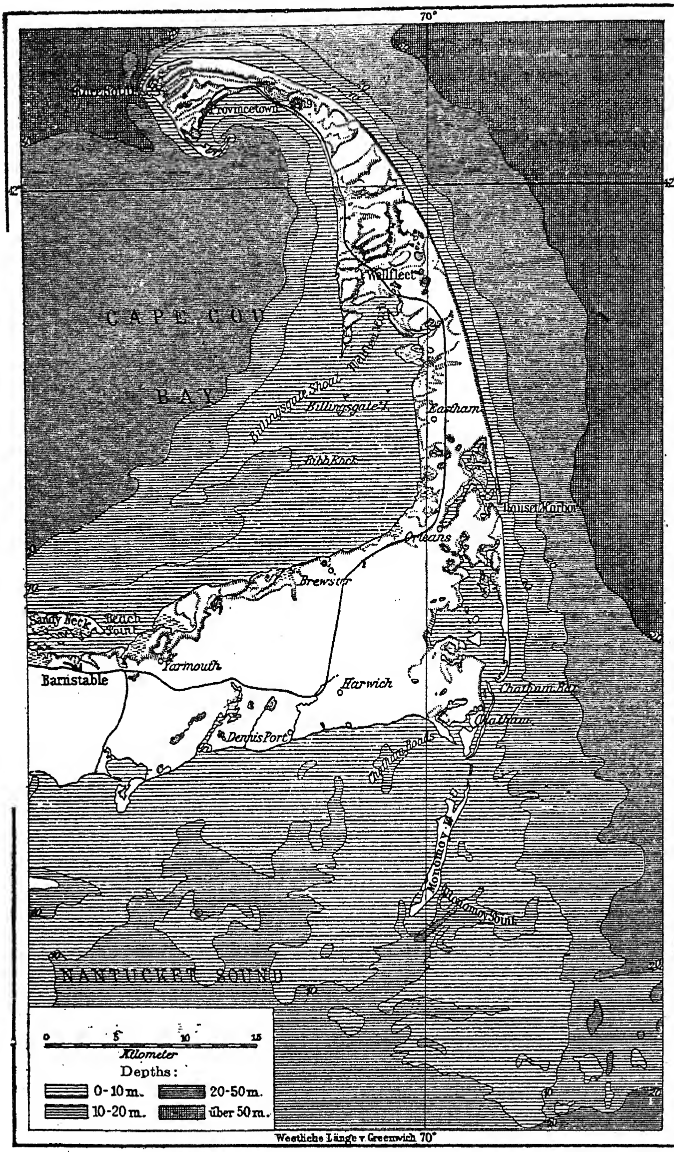


FIG. 714. — Map of Cape Cod, showing the long outer erosion cliff of the "Forearm," and the sand spits built from the sands thus eroded, both southward and northward, where they form the foundation of the dune headland of Provincetown. (After Coast Survey Chart, from Ratzel, *Die Erde.*)

These deposits of peat, etc., now begin to appear upon the shore, and as erosion continues, the entire new-formed series will be removed again. With the advancing sea, the water retains sufficient depth for efficient wave work, and when the lagoon deposits have been wholly removed, the original shore will be vigorously attacked, the water now being deep enough for this process. As the sea cuts inland like a horizontal saw, a sea-cliff is produced, which, because of the regularity of the coastal plain, will, other factors remaining inactive, be uniform and continuous. This cutting into the land may continue indefinitely if the tidal and other currents are strong enough to carry away the product of erosion. If not, a beach is formed at the foot of the cliff, and erosion eventually

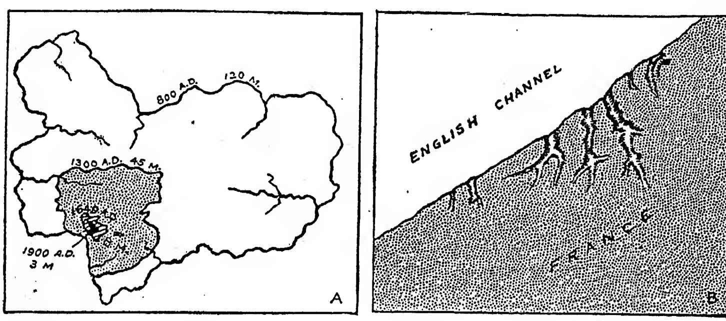


FIG. 715. — Work of the waves in cutting away rocky coasts. *A*. Successive stages in the destruction of the island of Helgoland. *B*. Cliffs of Normandy; the coast has been cut back so far that the tributaries of the old river systems now enter the sea independently. (After Lobeck, in *Military Geology*.)

becomes checked by the accumulation of a protecting belt of material. (See Fig. 446, p. 530, and Fig. 447, p. 531.) The bold Yorkshire coast of England, the Channel Coast of France (Fig. 713), and the long sand cliffs of the outer arm of Cape Cod on the Massachusetts coast (Fig. 714) illustrate the continued cutting of the sea into the land in regions which, in many respects, have the characteristics of coastal plain strata. One striking effect of such inward cutting on the coast is the betrunking of the streams which formerly ran down the slope of the coastal plain into the sea. Eventually, the main stream may be cut back so far that its former branches enter the sea as independent streams. Good illustrations of this are furnished by the Channel Coast of France. (See Fig. 715, *B*.)

Erosion of Coasts on Maturely Dissected Lands. — The coast of Maine and that of Sweden present typical examples of a relatively young coastline upon a maturely dissected drowned land. The numerous parallel river valleys have been converted into indentations, and the ridges between the valleys project into the sea as long spurs or rock tongues, and by the submergence of low places across them, numerous islands, aligned with the ridges, are produced. Travel along such a coast is possible only by boats; all roads and railroads must be placed far inland. Erosion (Fig. 711, p. 805) is restricted to the cliffing of the headlands and islands,

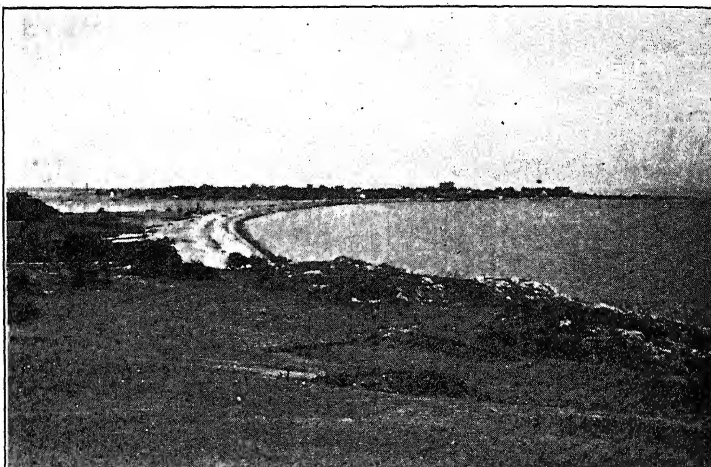


FIG. 716. — Marblehead Neck, Mass. A rocky island tied to the mainland by a narrow beach (or *tombolo*) of cobblestones and sand. (From D. W. Johnson's *Shore Processes*, John Wiley and Sons.)

but at the same time, the narrower and shallower indentations are bridged across by sand and gravel bars built by the waves, and rocky islands are tied to the main land by sand and pebble beaches (Fig. 716). Thus the coast is straightened, but the process is necessarily a very slow one, and a change of level may occur before it has proceeded far. If elevation takes place, there will appear abandoned sea-scarps inland, as well as abandoned beaches.

Where a normally dissected coastal plain is drowned, as on the coast of Maryland and New Jersey, the sea will enter the consequent river channels and wave erosion will widen the bays thus formed, as in the case of Chesapeake and other bays on the

Atlantic coastal plain. Where drowning has gone so far that the inner lowland is submerged, the cuesta of the coastal plain may be broken into islands, Long Island, New York, being an example of this. Here wave attack produces cliffs along the northern coast, which is the drowned inface of the cuesta, but on the southern coast, where the submergence has produced a new intersection of the sloping coastal plain and glacial outwash strata with the sea, erosion is preceded by bar-building and lagoon-filling.

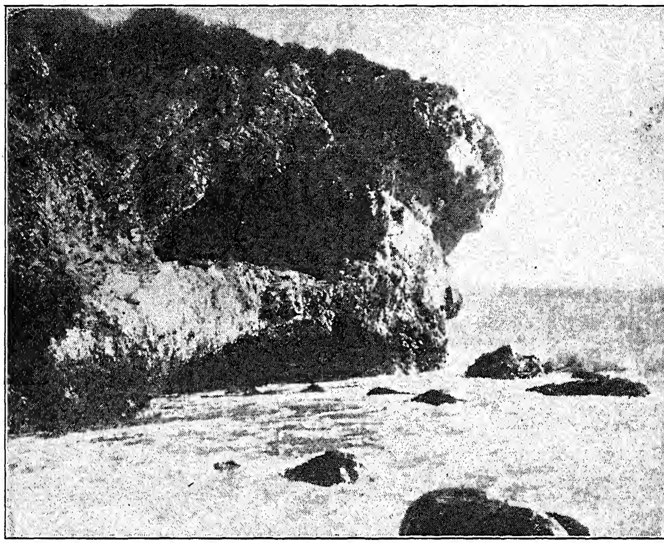


Fig. 717. — Sea-caves on the coast of California. An upper cave is shown which was cut when the land stood ten feet lower with reference to sea-level. (Photo by G. W. Stose, from U. S. G. S.)

Special Erosion Features

Stratified and Jointed Rocks. — Vigorous wave erosion on horizontally stratified rocks is apt to produce vertical cliffs, especially if the beds at the base are weak. By the attack of the waves sea-caves may be produced on softer strata (Figs. 717, 718), or by extensive undermining harder beds may form overhanging ledges until they break down from overweight. The formation of sea-caves is especially favored by joints which traverse the rocks vertically and permit the waves to cut along them. On the north shore of Lake Superior, an extensive series of such wave-cut caves

was formed in the soft sandstone of the Pictured Rocks. Many of these caves have since collapsed, but new ones are constantly form-

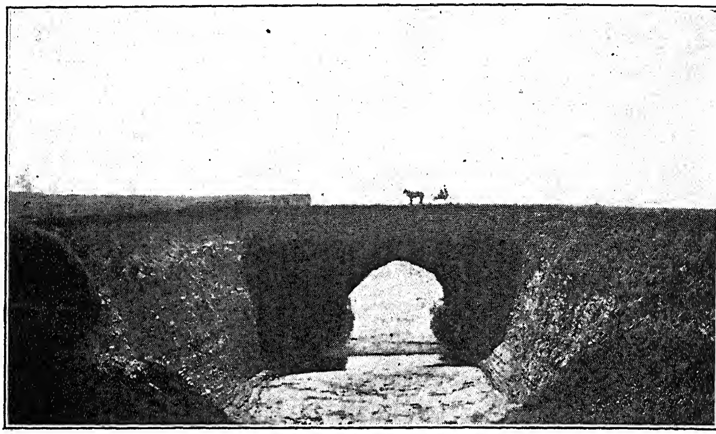


FIG. 718. — Wave-cut arch known as the Natural Bridge one half mile north of mouth of Medder Creek, Santa Cruz County, California. (U. S. G. S.)

ing. Caves of this kind are not uncommon on the British and French coasts, and in the past some of these served as the haunts of smugglers (Figs. 719 *a*, *b*). They are cut in other jointed rocks

FIG. 719 *a*. — Tilly Whim Caves. Elevated sea-caves cut by waves in horizontal (Jurassic) strata. Coast of English Channel, Durlston Head, south of Swanage, England.

as well, good examples being found on the basaltic coast of Nova Scotia, while Fingal's Cave on the Island of Staffa, west coast of

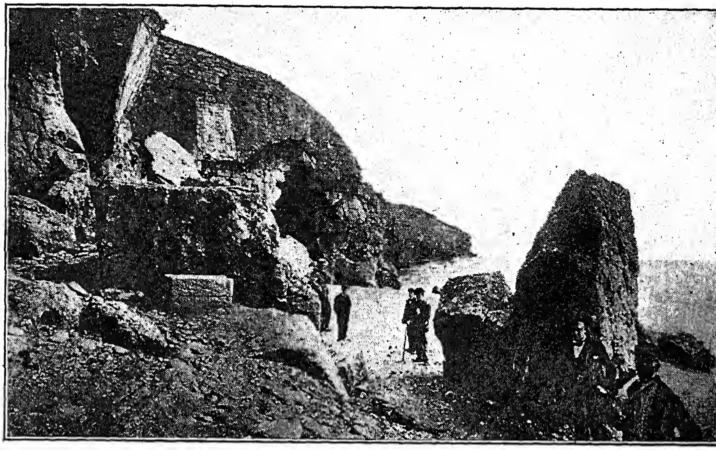


FIG. 719 *b.* — Tilly Whim Caves. Caves due to marine erosion in horizontal (Jurassic) rocks, coast south of Swanage, England.

Scotland, is a classic example of a wave-cut cavern of considerable depth in a jointed basaltic rock (Figs. 720, 721, see also Figs. 122 *a–d*, pages 178 to 179).

Caverns of this type are often found at some elevation above sea-level, as on

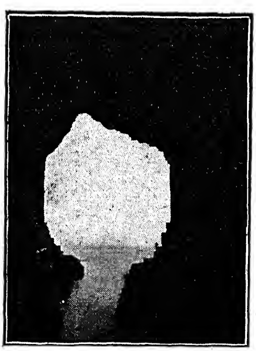


FIG. 720. — Fingal's Cave. Isle of Staffa, off west coast of Scotland. Looking seaward from within the cave. (Photo by author.)

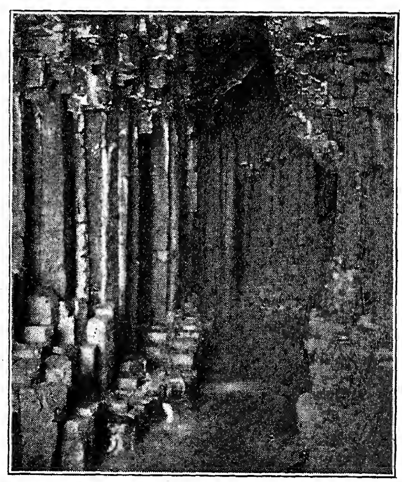


FIG. 721. — Interior view of Fingal's Cave, a sea-cave in columnar lava on the Island of Staffa, Scotland. (From D. W. Johnson's *Shore Processes*, John Wiley and Sons.)

the coast of the Island of Gotland in the Baltic, on the coast of Mackinac Island in Lake Huron (Fig. 722), and elsewhere. They indicate an elevation of the land or a subsidence of the water-level since their formation. (See also Fig. 717, p. 811.)

When joints are numerous and traverse the rock mass throughout, a series of ramparts may be produced, such a character being

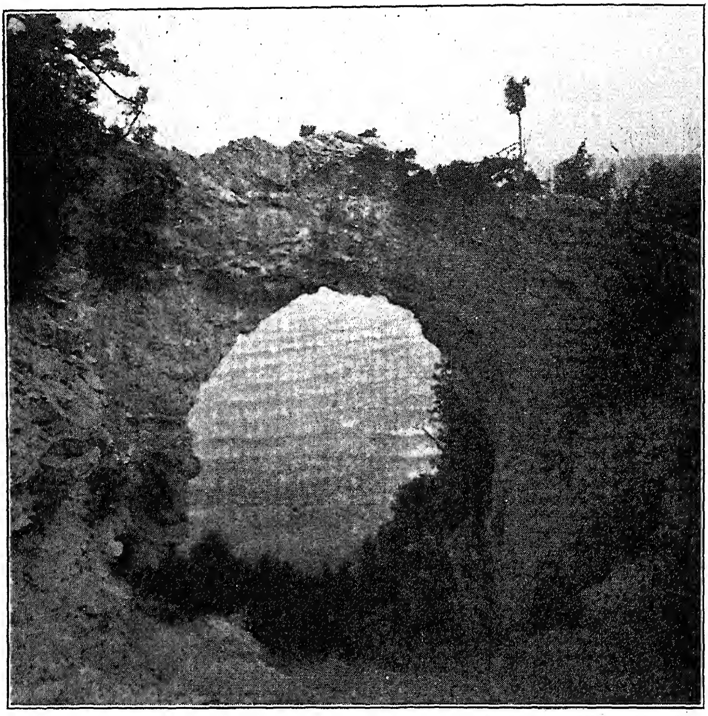


Fig. 722. — The Arch or Natural Bridge cut from brecciated limestone (Upper Silurian) by the waves of Lake Huron during a former higher level. The arch is the remnant of the roof of a wave-cut cavern.

especially well shown in the jointed sandstones along Cayuga Lake, New York (Fig. 564, p. 639). Isolated masses or sea-stacks may also be severed from the mainland in this manner. Such structures are especially marked on the coast of Scotland and the Orkney Islands, where the jointed and nearly horizontal Old Red Sandstone cliffs are rapidly succumbing to wave attack. Similar sea-stacks are formed (Figs. 723 *a*, *b*) from the chalk on the English coast and on the French coast (see Fig. 446, p. 530), and from the

basalt on the coast of Nova Scotia. Several ancient stacks are found on the northern shore of Lake Michigan, Lake Huron, and on Mackinac Island, marking a former higher level of the water.

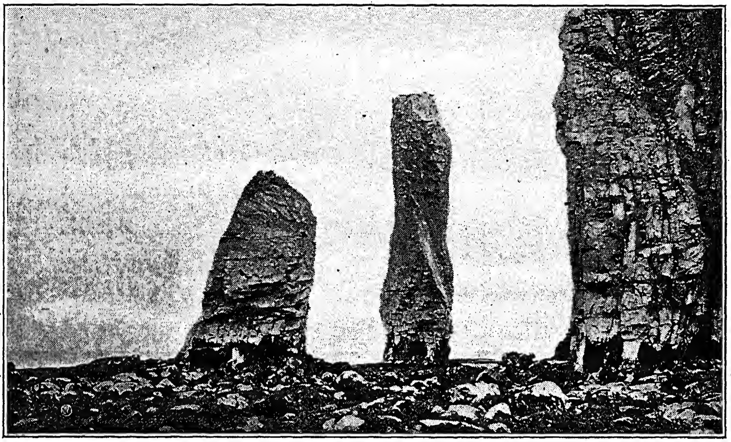


FIG. 723 *a*. — "Old Harry" and "Old Harry's wife." Sea-stacks cut by the waves of the English Channel from jointed chalk cliffs. The Foreland, north of Swanage, England.

They also abound in places on the coast of the island of Gotland at a level coinciding with that of the abandoned sea-caves.

Where stratified rocks are steeply inclined, their erosion on the

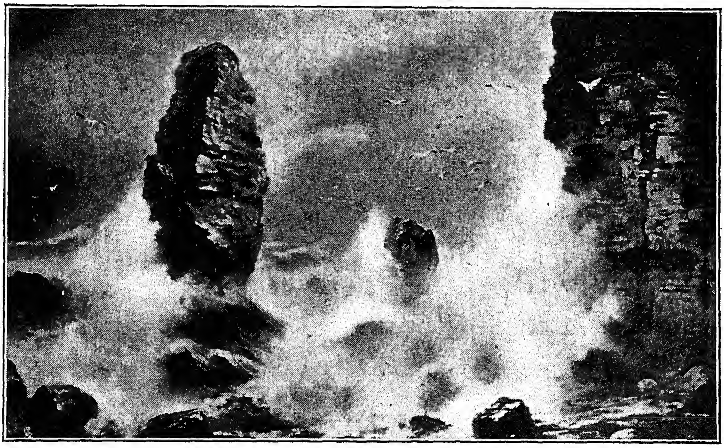
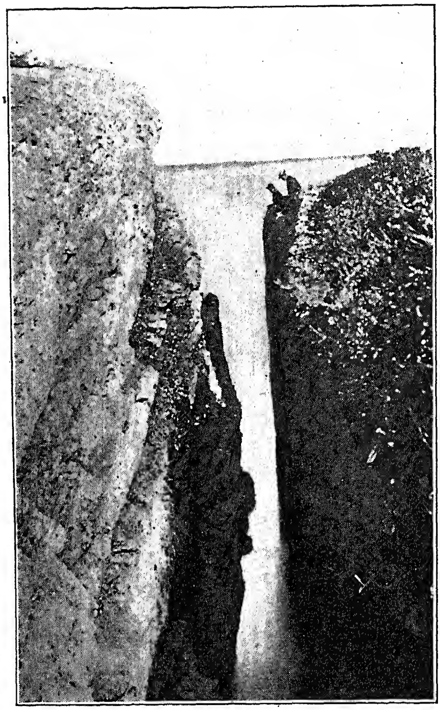


FIG. 723 *b*. — "Old Harry Rocks" and chalk cliff. Attacked by storm waves. Coast north of Swanage, England.

coast produces a series of "skerries" or reef-like ridges formed by the harder beds; when submerged they form dangerous shoals.

Igneous Rocks. — Except when fine-grained and much jointed, igneous rocks present a less favorable medium for cliff-cutting than do the stratified rocks. Wherever a fairly coarse granite forms the coast, wave erosion does not keep pace with the weathering of exposed parts of the mass, and the surface will thus often be rounded rather than abrupt. A part of this rounding may also be due to previous glaciation, as on our northern Atlantic coast, where the topography produced by the ice has not yet been destroyed by wave erosion. Such masses, if large, form a subdued rocky coast, even though exposed to very violent wave attack (Fig. 356 *a*, p. 429). Basaltic rocks, on the other hand, because of their excellent jointing, produce frowning cliffs, those of Nova Scotia and farther north, and those of the west Scottish coast, being typical examples.



Brown Bros.

FIG. 724. — Purgatory Chasm, Newport, R. I. A cleft in the conglomerate rocks due to erosion by the waves of a weathered zone between joint cracks. It simulates a chasm left by the erosion of a dike, and was formerly regarded as such.

Erosion of Dikes. — Along many of the cliffed portions of the New England and the British coasts, basaltic or diabase dikes which cut other strata and are exposed to wave attack have been removed by the loosening of the successive joint blocks into which such dikes are generally divided. As a result, a deep, narrow chasm is formed, with vertical sides if the dike was vertical (see

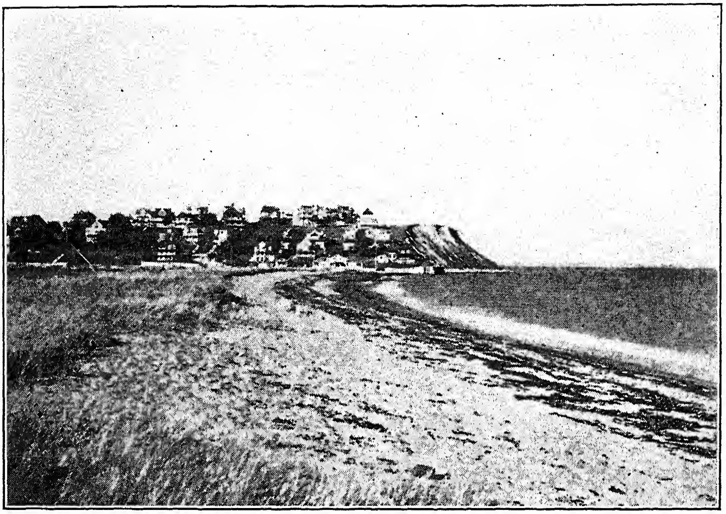


FIG. 725. — Winthrop Great Head, a drumlin near Boston, whose eastern end has been removed by wave erosion. In the foreground is a beach built from the eroded material. (Photo by D. W. Johnson.)

Fig. 135, p. 192), and at the end of such a chasm is often found a cavern-like hollow into which the waves dash, compressing the air, whereupon the water is forced out again with great force, producing various forms of waterspouts. When the jointing of the dike is not well developed, it is not so readily eroded, especially when the surface is gently sloping, in which case the surface of the dike will be even with that of the enclosing rock. Similar fissures may, however, be eroded in massive much-jointed rocks, along a weak zone, as is well illustrated by the chasm called Purgatory on the coast at Newport, R. I., which is worn along a weak zone in massive conglomerate (Fig. 724).

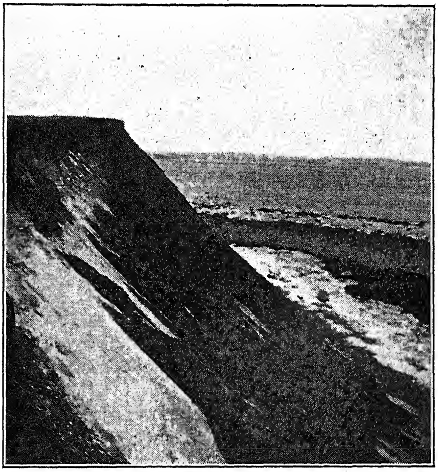


FIG. 726. — Grover's Cliff, Winthrop. An eroded drumlin on the Massachusetts coast.

Erosion of Glacial Deposits. — When unconsolidated glacial deposits are exposed along the shore, erosion by waves progresses on the whole very rapidly until it becomes checked by the accumulation of boulders which are left behind during the removal of the finer material. This is especially well shown where the terminal moraine of the last ice age is exposed upon the shore, as is the case along the south coast of Massachusetts at Woods Hole and the Elizabeth Islands and on parts of the shore of Long Island. In these regions the beach at low tide presents an accumulation of large boulders which are not readily moved by the waves. Drumlins also, when cut by the sea, are apt to be fronted by a boulder pavement (Fig. 447, p. 531) which greatly retards further erosion.

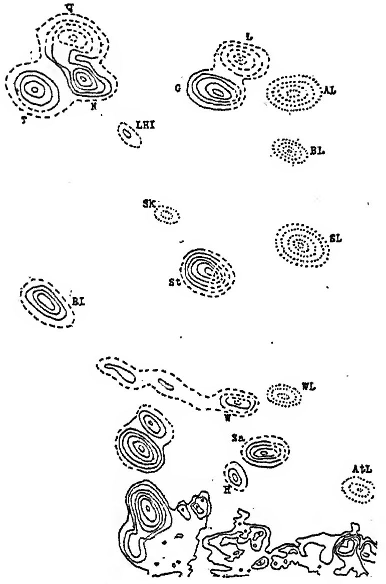


Fig. 727. — Development of Nantasket Beach. (After Johnson and Reed.) First stage, original drumlins restored. Restoration in dotted lines.

AL.	Allerton Lost Drumlin
AtL.	Atlantic Lost Drumlin
BL.	Bayside Lost Drumlin
BI.	Bumkin Island
G.	Great Hill
H.	Hampton Hill
L.	Little Hill
LHI.	Little Hog Island
N.	Nantasket Hill
Q.	Quarter Ledge
Sa.	Sagamore Head
Sk.	Skull Head
SL.	Strawberry Lost Drumlin
St.	Strawberry Hill
T.	Thornbush Hill
W.	White Head
WL.	White Head Lost Drumlin
WP.	Windmill Point Sand Spit

Drumlins cliffed by the sea present a very characteristic profile, which varies with the distance to which the drumlin has been cut back. Winthrop Head on the Massachusetts coast is a drumlin half of which has been removed by the sea. The profile there formed is shown in the illustration (Fig. 725). A near view of the profile of an eroded drumlin cliff from the same coast is shown in Fig. 726. The sands worn from

the drumlins are partly used in the building of the beach shown in the foreground of Fig. 725. Because of the abundant supply of such sands, extensive bars and spits are produced by the long-shore currents and the waves, and these frequently tie rocky islands to the main shore, as in the case of Nahant, which is tied by a long sand beach to the Massachusetts coast at Lynn. Formerly isolated drumlins, more or less eroded by the sea, may thus be tied together

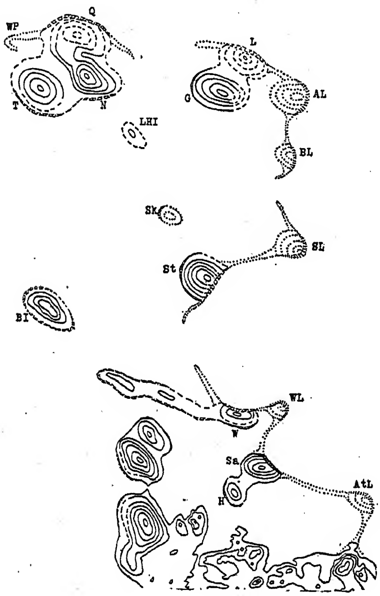


FIG. 728 *a*. — Development of Nantasket Beach. (Johnson and Reed.) 2d stage. Early erosion and connection of some of the drumlins by bars or tombolos. (For notation see Fig. 727.)

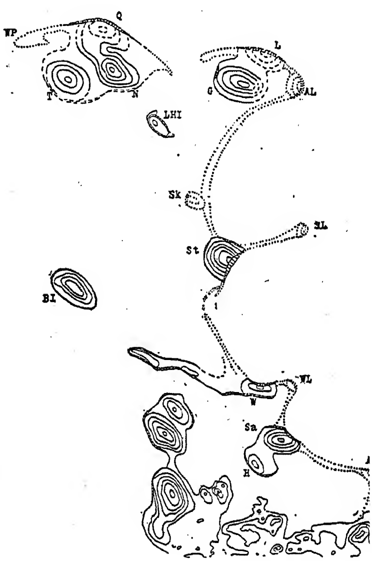


FIG. 728 *b*. — Development of Nantasket Beach. (Johnson and Reed.) 3d stage. Further connection of eroded drumlins by beaches (tombolos). (For notation see Fig. 727.)

by sand beaches, as has been the case on the Massachusetts coast, in the formation of Nantasket beach. Here beaches have in some cases been built so rapidly that the old cliffs have been protected from further erosion, and thus drumlins in various stages of dissection, but now some distance inland from the shore, enter into the construction of this remarkable land-mass. The successive stages in the formation of this beach are shown in the maps here reproduced from the studies of D. W. Johnson and W. G. Reed, Jr.

(Figs. 727 to 730). Extensive sand spits and bars are also built along the outer coast of Cape Cod (Fig. 714), where the waves cut away the unconsolidated stratified drift of fluvio-glacial origin and carry it both southward and northward. On the north they have built a succession of bars on which the sands have been piled up into dunes by the wind to form the headland of

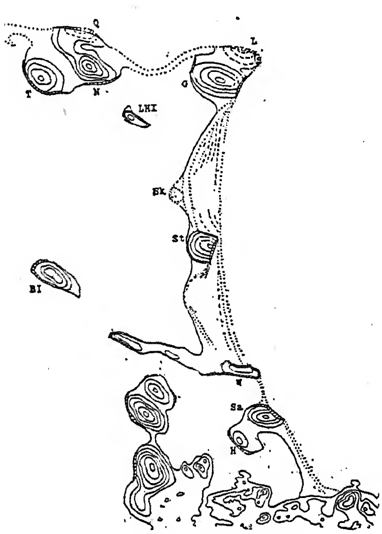


Fig. 729 *a*. — Development of Nantasket Beach. (Johnson and Reed.) 4th stage. Development of beach-ridges and beach-plain. (For notation see Fig. 727.)

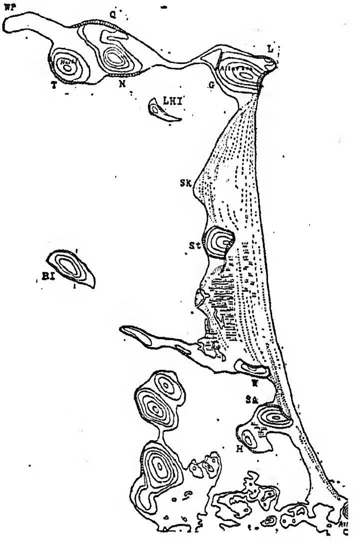


Fig. 729 *b*. — Development of Nantasket Beach. (Johnson and Reed.) 5th stage. The modern beach, consisting of old cliffed drumlins with broad beach-plain in front of it. (Notation as in Fig. 727.)

Provincetown. The seaward face of the forearm, subject to constant wave erosion, presents a continuous and regularly curving line of cliffs with scarcely any break for many miles. Where clays are present in the sands, as at Highland Light, the cliffs present picturesque erosion features due chiefly to rain-wash (Fig. 731).

Erosion Forms Produced by Atmospheric Agencies

The atmospheric agencies, under which are classed the diurnal and seasonal changes of temperature; the moisture and gases of the air and the activities of frost, rain, and wind, produce erosion

forms essentially peculiar to themselves. Some of these have already been mentioned, but they may again be briefly referred to, while others not yet noted may be added. Several of these agents generally act in conjunction, and their individual activities cannot always be dissociated.

The Cliff and Talus. — These are primarily the products of temperature changes and frost work. The fragments broken by these agents from the face of the cliff will accumulate at its foot to form the talus, the slope of which is in general harmonious with the size and other characters of the fragments. When not removed by the agents of denudation such a talus may accumulate until it mantles much if not the whole of the cliff-face. Old talus surfaces are generally overgrown with forests if the climate is sufficiently moist. Mountains exposed to much frost action, but not covered by glaciers, are generally characterized by extensive accumulations of broken fragments, which may entirely mask the underlying ledges. This is the case to a considerable extent in the White Mountains of New Hampshire, in Pikes Peak, in Ben Nevis in west Scotland, and in other mountains like these. In some cases these fragments give to the summit a remarkably perfect conical form.

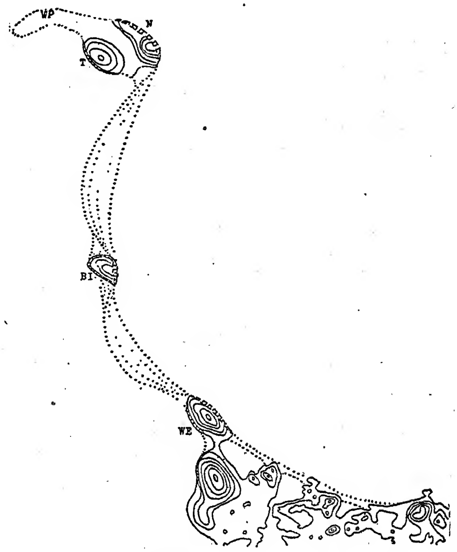


FIG. 730. — Development of Nantasket Beach. (Johnson and Reed.) A hypothetical future stage. The outer drumlins are all worn away and the beach extends from the rocky ridges at Nantasket (Atlantic) to World's End drumlin (*WE*); thence to Bumkin Island (*BI*) and thence to Nantasket Hill (*N*) in Hull. (For notation see Fig. 727.)

Sculpturing by Rain and Atmospheric Moisture. — The earth pillars of Colorado and of Bozen in the Tyrol (Figs. 345 *a*, *b*, pp. 411, 412) have already been referred to as products of rain erosion. Where cliffs are composed of soft clays or shales, or of soluble material,

fantastic shapes will be carved by the rain (Fig. 731) or produced by a process of solution, this being especially marked in certain elevated limestone peaks in which, if the strata are inclined, a strikingly fretted upland surface is produced (Fig. 346 *b*, p. 413). Remarkable solution forms are also produced upon the surfaces of salt mountains, such as those of Cardona, Spain, and of southern Persia. The salt pillars of the Dead Sea, which have given rise to the legend of the transformation of Lot's wife into salt, are likewise the products of subaërial sculpture upon an ancient cliff of salt.

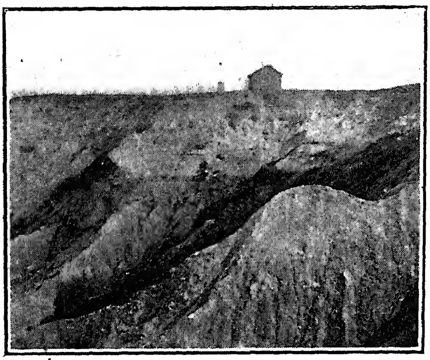


FIG. 731. — Clay cliffs at Highland Light, Truro, on Cape Cod, showing characteristic erosion forms due to rain and wind.

Sculpturing Process of Wind. — The sculpturing process of wind comprises both deflation of material loosened under the influence of the weather, and active corrasion of the rock surface by the sand-blast. By the combined action of these processes, wind-carved structures, often of remarkable form, are produced. We have already referred to the faceted pebbles or "dreikanter" which represent faces carved by the sand-blast upon partly exposed pebbles in regions of much sand-drifting (p. 406). But structures of a much larger type are also produced by wind erosion. Such are the natural monuments carved from soft sandstone of uniform grain in the plains about Pikes Peak, Colorado, and which are generally capped by a projecting mass of more resistant sandstone due to cementation of the grains by iron oxide (Fig. 340, p. 407). The great sandstone buttes which dominate the Plains country in various regions in western North America (Fig. 344, p. 410, and Fig. 599, p. 701) are much larger examples of such erosion remnants left after much of the rock formerly continuous with them had been removed by stream and by eolian erosion.

But by far the most striking products of stream and eolian erosion, supplemented in part by other agencies of denudation, are seen in the wonderful sandstone arches or natural bridges

found in several localities within the semi-arid district of southern Utah and other regions (Fig. 732). One of these, the Rainbow or

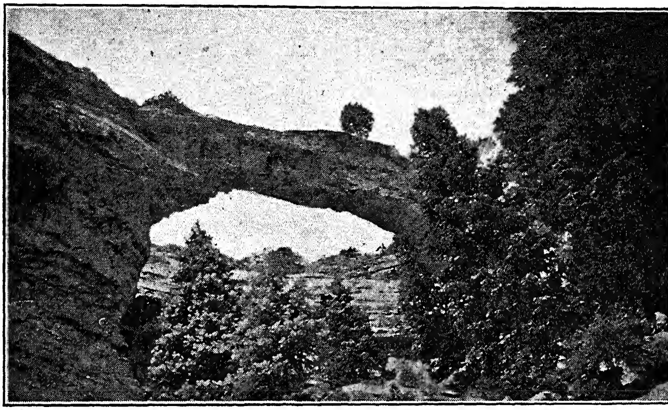


Fig. 732. — Natural Bridge, or sandstone arch formed by stream and wind erosion. Utah. (F. J. Pack, photo.)

"Barohoini" Natural bridge of southern Utah, has a height of 398 feet, a width between abutments of 278 feet, and is 33 feet

Fig. 733. — Looking-Glass Rock; a mass of sandstone carved and hollowed by erosion. The size is indicated by that of the white horse in the left foreground, and that of the two men in the rear opening. Near La Sal Mountains, Utah. (Whitman Cross, photo; from U. S. G. S.)

wide at the top. Another rock-form due chiefly to wind erosion is seen in Looking-Glass Rock near La Sal Mountains, Utah (Fig. 733).

In arid regions these products of subaërial erosion are numerous and present such a bewildering series of fantastic shapes that even the most prosaic are beguiled into comparisons with organic forms, while the more imaginative here find the prototypes of all the fanciful creations of fairy-tale and folk-lore.

The sculpturing processes create the landscape as we see it; they supplement the constructional and deformational processes, and it is they that are primarily responsible for the diversified nature of the earth's surface, and for the great variety of habitats in which the multifarious types of plant and animal life find a momentary place of occupancy, during the ceaseless procession of organic forms upon the earth. Finally, it is the sculpturing processes which bring about the never-ceasing changes in the contours of the face of the earth, which like the changing human countenance is never the same from day to day, though we, with our limited power of vision, are able to perceive only the more pronounced and abrupt of these modifications.

> The hills are shadows, and they flow
> From form to form, and nothing stands;
> They melt like mist, the solid lands,
> Like clouds they shape themselves and go.

Fig. 734. — Alexander von Humboldt. The first great leader in the study of land forms, their origin, and the adaptation of organisms to them. (From the portrait by Schrader. Guyot's *Physical Geography.*)

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Figures in *italics* refer to pages where descriptions or definitions are given; figures followed by an asterisk (*) refer to pages on which illustrations are given. Generic and specific names are in italics.